



PHD

Carbon and ecological footprints for the 21st century

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Award date:
2010

Awarding institution:
University of Bath

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CARBON AND ECOLOGICAL FOOTPRINTS FOR THE 21ST CENTURY

Evaluating the significance of North-South affluence and
population growth

Gemma Rose Cranston

A thesis submitted for the degree of Doctor of Philosophy

University of Bath
Department of Mechanical Engineering
August 2010

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SUMMARY

Environmental and carbon footprints have recently come to the fore of the media's, governmental and general public's attention. They offer an excellent indication of humanity's demands upon Nature and allow evaluation of ecological deficit by contrasting supply and demand. The ecological debt many nations find themselves in is unsustainable, globally inequitable and adds to the growing effects of climate change. These footprints need to be further investigated, looking at historic and future trends in order to better understand, not only the global overuse of natural capital, but also the imbalance between nation states of the world. The value and limitations of the footprint must be recognised; the footprint alone cannot represent the full anthropogenic impacts upon the Earth.

This thesis focuses on developing the definitions of the ecological and carbon footprints, analysing the significant factors that affect their composition. The selected parameters are diverse, ranging from a host of economic, geographic and climatic factors. It is shown that both the carbon and ecological footprints are primarily driven by economic welfare, a result that reflects the consumptive nature and fundamental basis of the footprint. Analysis of the resultant correlating equations, for both the environmental and carbon footprints, highlights the differences between the developing and industrialised world in terms of their profligate or frugal use of Nature's resources. This concludes the stark contrast between these regions of the globe in terms of their per capita and total footprint values.

The disparity between the populous South and the prosperous North is further investigated to the year 2100, with the use of Intergovernmental Panel on Climate Change's scenarios and adaptation of the correlating ecological footprint equation. Four separate scenarios are adopted, each having different underlying assumptions regarding economic development, demographic transition and environmental awareness for various regions of the world. For all scenarios the Southern regions rapidly increase their levels of total ecological footprint; in contrast the industrialised world maintains a relatively conservative evolution. Although different scenarios suggest contrasting future pathways, the hope of contraction and convergence among global footprint levels is not completely lost.

The intensification of carbon emissions from both the affluent North and the majority South are considered with respect to population, economic and energy use trends from 1900 to the end of the twenty-first century. It is overwhelmingly shown that affluence will drive growth in carbon emissions across the world by the end of the century.

Global inequality must be reduced; the footprint is utilised to demonstrate the trends in resource misuse and contrast between the ecological debtors and ecological creditors of the world.

ACKNOWLEDGEMENTS

Many thanks to my supervisor Geoff Hammond for his support throughout my PhD and enabling me to undertake the many opportunities that have arisen. I would like to thank Marcelle McManus for her guidance and help along the way, and thank everyone in the 'Sustainable Energy Research Team' at the University of Bath who have made my working life so enjoyable. Thank you so much to Gary Lock, whose continued encouragement has been a constant source of inspiration.

Special thanks to my mum who has the patience of no other, never ending encouragement and has provided me with innumerable 'pep' talks. Thank you so much for your love and support, and being there when I really needed you.

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GLOSSARY

Carbon Footprint	The demand on biocapacity required to sequester (through photosynthesis) the carbon dioxide emissions from fossil fuel combustion that is not absorbed by the ocean
Ecological Footprint	A resource accounting tool that measures how much biologically productive land and water area an individual, a city, a country, a region, or humanity uses to produce the resources it consumes and to absorb the waste it generates, using prevailing technology and resource management
Equivalence Factor	A productivity based scaling factor that converts a specific land type to a global hectare
Global Hectare	A standardised average productive hectare - one global hectare is equivalent to one hectare with productivity equal to the average productivity of the available bioproductive land on Earth
<i>Harmonized scenario</i>	Harmonized scenarios within a family share common assumptions for global population and GDP
<i>Illustrative scenario</i>	A scenario that is illustrative for each of the six scenario groups. They include four "scenario markers" for the scenario groups A1B, A2, B1 and B2, and two additional illustrative scenarios for the A1FI and A1T groups
<i>Marker scenario</i>	A scenario that was originally posted on the SRES web site to represent a given scenario family. A marker is not necessarily the median or mean scenario
Natural Capital	All of the raw materials and natural cycles on Earth; the stock of living ecological assets that yield goods and services on a continuous basis
<i>Other scenarios</i>	Scenarios that are not harmonized
Overshoot	Overshoot occurs when humanity's demand on Nature's exceeds the biosphere's supply

Scenario	A description of a potential future, based on a clear logic and a quantified storyline
Scenario <i>Family</i>	Scenarios that have a similar demographic, societal, economic and technical-change storyline. Four scenario families comprise the SRES: A1, A2, B1 and B2
Scenario <i>Group</i>	Scenarios within a family that reflect a variation of the storyline. The A1 scenario family includes three groups designated by A1T, A1F1 and A1B that explore alternative structures of future energy
Scenario <i>Storyline</i>	A narrative description of a scenario (or a family of scenarios) highlighting the main scenario characteristics, relationships between key driving forces, and the dynamics of the scenarios
<i>Standardized scenario</i>	Emissions for 1990 and 2000 are indexed to have the same values
Yield Factor	A factor that accounts for differences between countries in productivity of a given land type

NOMENCLATURE

C	Carbon dioxide emissions, GtC
<i>cf</i>	Per capita carbon footprint
CO₂	Carbon Dioxide
CO_{2eq}	Carbon Dioxide Equivalent
CR	Carbon ratio, µg C/J
C_w	Carbon Weight
<i>ef</i>	Per capita ecological footprint
EI	Energy intensity, MJ/\$
EQF	Equivalence Factor
F	Carbon intensity, GtC/\$
FAO	Food and Agriculture Organization
FR	Fertiliser Ratio
G	Per capita GDP, \$/cap
GDP	Gross Domestic Product
gha	Global Hectare
GHG	Greenhouse Gases
GNI	Gross National Income
HDI	Human Development Index
HS	Harmonised Scenarios
IEA	International Energy Agency

IIASA	International Institute for Applied Systems Analysis
IPCC	Intergovernmental Panel on Climate Change
IR	Irrigation Ratio
L	Latitude
MEX	Market Exchange Rates
OECD	Organisation for Economic Co-operation and Development
OR	Overshoot Ratio
OS	Other Scenarios
P	Population
PD	Population Density
PPP	Purchasing Power Parity
PR	Precipitation Ratio
SF	Soil Fertility Ratio
SRES	Special Report on Emission Scenarios
Tech R	Technology Ratio
Temp R	Temperature Ratio
Terr	Terrain Ratio
UN	United Nations
UNDP	United Nations Development Programme
UNEP	United Nations Environmental Programme
WBCSD	World Business Council for Sustainable Development

WWF	World Wide Fund for Nature
Y_F	Yield Factor
Y_N	National Average Yield
YR	Yield Ratio

CHAPTER 1

THE BOILED FROG SYNDROME

*‘A frog placed in slowly heating water will not notice the gradual but eventually lethal trend’
(Wackernagel & Rees, 1996)*

1.1 BACKGROUND

Ever since the publication of ‘An Essay on the Principle of Population’ by Thomas Malthus (2005), originally published in 1798, there have been concerns that the human population is in danger of growing beyond the carrying capacity of the Earth (Rapport, 2000). Ecological footprinting is a way of illustrating humanity’s impact on the planet. It can be used as a measure of how far a population is moving along the path to sustainability.

The currently accepted level of high development has been shown to be far from the level required for sustainable development. As countries improve the well being of their people, they bypass sustainability and enter into what is known as ‘overshoot’. It is thought that by continuing along this path, poor countries will be restricted in their development and rich countries will not maintain their prosperity.

1.2 THE FOOTPRINT

Footprint analysis is a useful tool that can compare environmental performance between nation states and provide an indication of how these states are moving along a sustainable development pathway. This thesis discusses some of the fundamentals of the footprint, and makes original contributions not only in breaking down the footprint in terms of influential determinants, but also applying these relationships to global situations and scenarios, both historic and futuristic. The distinct differences and inequalities between the populous South and prosperous North is discussed with reference to their current and future ecological footprints and carbon emissions, considering a variety of pathways the world may follow towards a sustainable and equitable globe.

The need for change and the imbalance between differing regions of the world is made clear throughout. Adaptation, mitigation and technology transfer are all important to enable global emission reductions and prevent further climate change. Many have advocated the ‘technological fix’ but this has historically only occurred as a result of conflict resolutions. Take medicine as an example, where anaesthesia and antiseptics were rapidly developed throughout periods of war, or aviation, where the power of flight was dramatically enhanced during the First World War. Historically there has been an impetus for change, whether this will be economically driven or pushed by

evidence of ever worsening disasters and serious global threats, it remains that change and adaptation is necessary to reduce the risk of further irreparable damage to the environment.

1.3 ECOLOGICAL FOOTPRINT ANALYSIS

Sustainable development is necessary for growth in an equitable way, respecting Nature's limited resources. There must be a balance between the prosperous North and majority South, such that developing countries are allowed to grow. The ecological footprint can be used to assess the position of nations as they move towards sustainable development. Ecological footprint analysis allows comparison to the biophysical resources that can be generated each year, giving an assessment of ecological debt or credit. Much like the 'boiled frog', humanity may be unable to detect the gradual but deadly trend in which population and economic growth threaten civilisation and planet Earth.

1.4 AIMS AND OBJECTIVES

In order to develop understanding and assess the benefits of the footprint the primary aims of the research undertaken within this thesis are:

- Aim 1:** To assess the fundamentals of the footprint, in terms of determinants that influence its size and growth.
- Aim 2:** To compare and contrast the differences between the developing and industrialised worlds in terms of their footprints and carbon consumption not only currently but also in the past and into the future.

These aims are inter-linked and can be considered in conjunction with one another. In order to achieve these aims, a set of objectives were defined:

- Objective 1:** Define Sustainable Development (Chapter 2).
- Objective 2:** Outline the fundamentals of the footprint in order to grasp the important concepts, methodologies and assumptions behind footprint formulation (Chapter 3).
- Objective 3:** Discuss the use of ecological overshoot and the imbalance between nation states across the world, in order to set in context the discussions surrounding the developments of the majority South and prosperous North (Chapter 4).
- Objective 4:** Assess the use of scenarios in examining future sustainability and identify appropriate scenarios for use in analyses (Chapter 5).
- Objective 5:** Identify driving forces for the footprint; analyse key determinants and establish a relationship between the *per capita* environmental (and carbon) footprint and these factors (Chapters 6, 8 and 9) through the use of dimensional analysis and multi-linear regression (Chapter 7).

Objective 6: Establish future pathways for the industrialising and industrialised worlds up to the year 2100 through the use of footprints (Chapter 10) by adopting scenarios (Chapter 5) and through development of the correlating equation (Chapter 8).

Objective 7: Ascertain the key contributors to growing carbon emissions in the populous South and affluent North over a 200 year period (Chapter 11).

This thesis consists of a variety of individual studies, all of which are related and linked together. Key findings are concluded at the end of each chapter, and Chapter 12 discusses these points coherently and cohesively.

1.5 OVERVIEW OF THESIS

A correlating 'power-law' equation is developed that demonstrates the relationship between the *per capita* ecological footprint and a wide range of determinants, varying from population to affluence to climatic factors (Chapter 8). Analysis of this type has been undertaken previously before by Hammond (Hammond, 2006a) where the footprint was compared to four determinants: population, national income, energy intensity and carbon emissions. The work in this thesis re-examines these issues but employs a far wider range of possible dependent variables and more recent data sets. Therefore, this work's original contribution is the inclusion of a host of varied parameters, considering the footprint beyond the limitations of the IPAT equation and analysing footprint fundamentals and drivers far deeper than has previously been explored. The consumptive nature of the footprint is reflected by the 'power-law' correlating equation, with a strong relationship between economic wealth and *per capita* national ecological footprint. Population density is proven to be the only other significant factor since all other parameters were found to be insignificant or had to be eliminated from the final equation to prevent double counting, for the year 2003. By highlighting the G8+5 nation states, individual country's consumption patterns are indicated and their profligate or frugal use of Nature's capital demonstrated. Analysis concerning the ecological debt of these countries is also demonstrated, illustrating the resource deficit many countries find themselves.

This methodology is also applied to the carbon footprint (Chapter 9). The influence of economic wealth, population density and pollutant emission intensity upon the carbon footprint are considered and developed into a correlating 'power-law' equation, building upon the work of Cranston *et al.* (2010) (Chapter 8). In the same manner as the ecological footprint, here the carbon footprint is proven to be dependent upon economic wealth, but also strongly related to energy intensity and carbon ratio. Improvements in these ratios through the development of technologies, methods and policies could lessen the impacts upon the biosphere and reduce the level of carbon emissions. The way in which nation states are wasteful or sparing with their resource use is illustrated by highlighting the G-20 nations; it is subsequently concluded that the economically

prosperous should lead the way and pave the pathway for transitional and developing countries to follow. As the transitional countries grow in geopolitical power and mature economically, it will become vital to assess how best to implement action against climate change; there must be a commitment from both the industrialised and developing world.

It is shown that the common representation of the carbon footprint is not a footprint at all, but a mass or 'weight' (Chapter 9). The significance of this fundamental difference is analysed. The 'carbon weight' is proven to have a very similar value to the carbon footprint, due to the conversion factor of approximately 1.

The development of the footprint into the future is considered in Chapter 10. The correlating equations from Chapter 8 are adapted alongside Intergovernmental Panel on Climate Change (IPCC) scenarios to discuss four different pathways into the future. The prosperous North and populous South are compared and contrasted to the end of the century. This work is unique since it builds upon the work and subsequent equations developed in Chapter 8 and Cranston *et al.* (2010). Currently the affluent North have far higher *per capita* national footprint values, however, it is shown that as the majority South develops it will rapidly overtake the North in terms of the magnitude of the footprint. The four marker scenarios that are considered have a variety of characteristics, ranging from positive environmental benefits and international connectivity to far more pessimistic outlooks with very little interregional collaboration or environmental consciousness resulting in extremely high footprint values.

The significance of various contributing factors to the emission of carbon dioxide is analysed within Chapter 11. The impact of population and economic welfare are of particular interest and are considered from 1900 to the turn of the 22nd century. The significantly different population and affluent levels are contrasted within the developing and industrialised countries. This work is novel since it undertook such a large timescale highlighting the disparity in the trends and patterns across these different regions. Population and economic wealth are proven to have been key drivers influencing the increases of CO₂ emissions for the developing world; however the focus upon both these drivers changes in the 21st century, moving solely to economic welfare such that population is no longer shown to be a strong driving force. In contrast the industrialised world's CO₂ emissions are driven by wealth throughout the entire 200 year period. Growth in carbon emissions is proven to be limited by the improvements in carbon ratio and energy intensity.

1.6 THESIS STRUCTURE

This thesis is divided into thirteen chapters. The thesis is structured such that the footprint is introduced in an informative and detailed manner in the first four chapters, outlining the basics behind the formulation of a footprint and how it can analyse the use of Nature's resources. These chapters are then referred back to within the analysis chapters of core research. From the introductory chapters the thesis details the fundamental methodologies utilised in the research, which again are referred to within the analyses section. Four major pieces of work were undertaken within this thesis and having used the structure of the thesis to set these in context through the introduction and methodology chapters, they are described in detail. The results chapters are brought together in Chapter 12 where they are discussed collectively.

In summary, Chapters 1-4 introduce the footprint; Chapters 5-7 contain the methodology and scenarios applied for the detailed analyses that are presented in Chapters 8-12. Chapter 13 concludes the thesis. This is illustrated schematically in Figure 1-1.

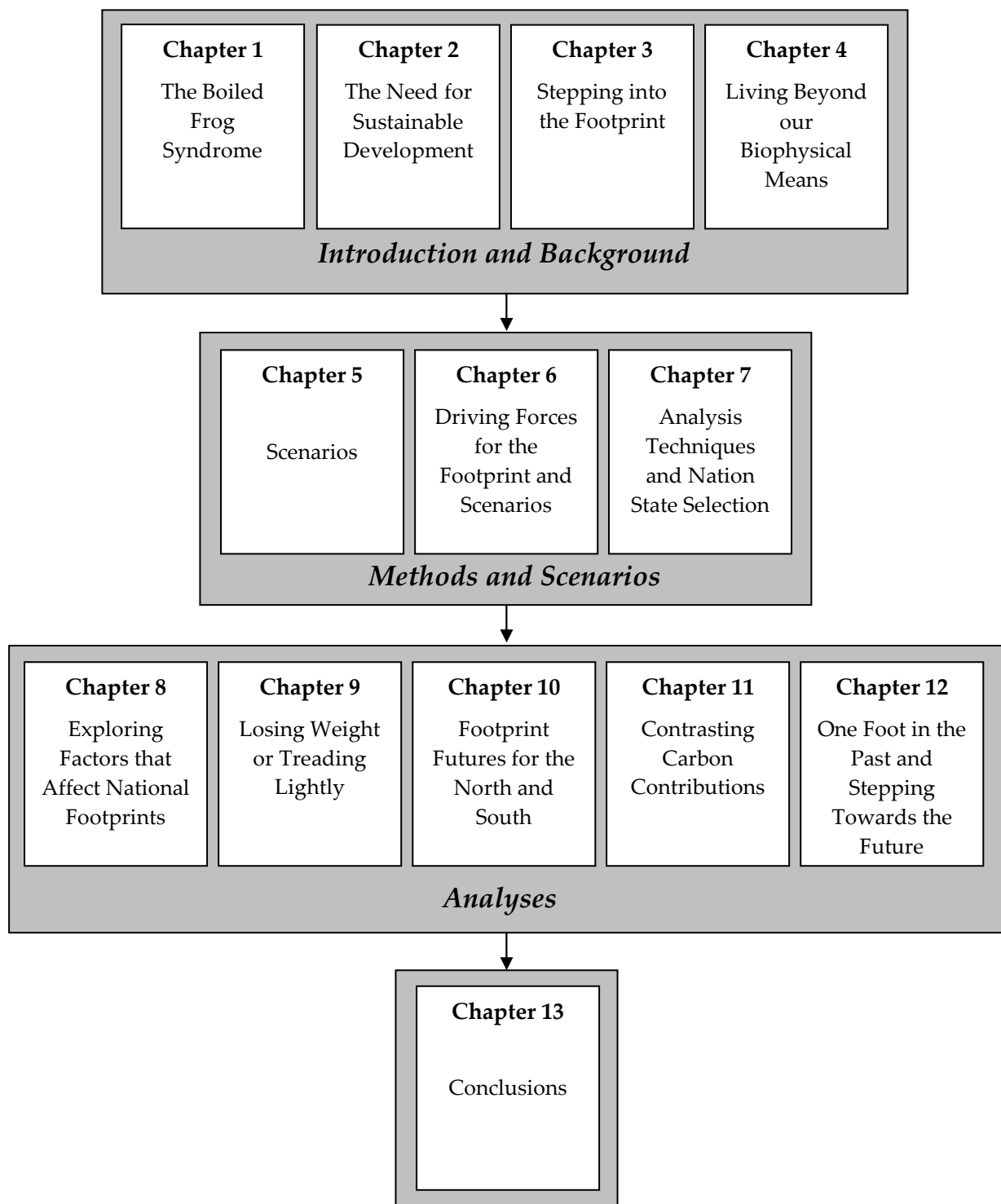


Figure 1-1: Diagram of thesis structure

1.7 PUBLICATIONS

The author's work has been published, to date, by Cranston *et al.* (2010), Cranston & Hammond (2010a) and Cranston & Hammond (2010b). These are reproduced in Appendix A. At the time of writing this thesis a further paper is in preparation for publication by Cranston & Hammond (2010c).

The contribution of the author's to these published papers was significant. As corresponding author, the research and majority of the writing within each paper was undertaken by Cranston. Thanks to Prof Hammond for his helpful insight and contributions as co-author.

CHAPTER 2

THE NEED FOR SUSTAINABLE DEVELOPMENT

'Global warming could make big tobacco [companies] look like small beer, because as well as harm done to individuals, whole nations could fall victim'
(Simms, 2005)

2.1 CLIMATE CHANGE CAUSE FOR CONCERN

Global warming and climate change are concepts with which the general public have become familiar. Many people are now concerned about the issues these physical phenomena raise, others are dismissive or sceptical, whilst some take the very pessimistic view that the planet is doomed.

Climate change is driven by shifts in the energy balance of the climate system, caused by changes in atmospheric concentrations of greenhouse gases (GHGs), land cover and solar radiation (IPCC, 2007b). Global warming is the phenomenon whereby the blanket of carbon dioxide around the Earth's surface increases, causing the planet to become warmer than it would otherwise be (Houghton, 2009), in much the same way as a gardener's greenhouse. These increased temperatures cause a larger amount of water vapour to collect in the atmosphere which also acts as a warming agent; this works alongside the growth in emissions of other gases such as methane, which also contribute to the problem. The rising temperature has many negative impacts, leading to significant climate change and effects around the globe.

The release of anthropogenic emissions is causing the planet to warm up; this warming of the planet has been attributed to the global average net effect of human activities since 1750 (IPCC, 2007b). The IPCC (Intergovernmental Panel on Climate Change) (IPCC, 2007c) have stated that:

"Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level."

The IPCC have determined that the observed increase in global average temperatures since mid-20th century is 'very likely' due to the increases in anthropogenic GHG concentrations (IPCC, 2007b). Indeed, it has been shown that global atmospheric concentrations of CO₂, CH₄ and N₂O have substantially increased due to human activities since 1750, such that these concentrations significantly exceed pre-industrial values established from ice cores (IPCC, 2007b). In the period 1970 to 2004 alone,

anthropogenic GHG emission increased by 70% from pre-industrial levels (IPCC, 2007b). It has been suggested that without changing the current trajectories, the world may go through the warmest period for at least the last 1000 years, possibly the last 100,000 years (Mitchell *et al.*, 2006). This chapter aims to introduce the concept of climate change and to define sustainable development.

2.1.1 Effects of Climate Change

The IPCC have undertaken detailed assessments of the global impacts of climate change, see for example IPCC (2007b). These include the possibility of extreme events, such as storms, heavy rainfalls, heat waves and coastal flooding (Mitchell *et al.*, 2006). As well as the increased frequency of these events, other catastrophes are expected to have huge impacts on the environment, including the melting of ice sheets and the release of large amounts of methane – which could in turn create a further increase in global warming (Mitchell *et al.*, 2006).

An assessment of the data since 1970 has highlighted the likelihood that anthropogenic warming has had a discernible influence on many physical and biological systems (IPCC, 2007d). Periods of extreme warmth could have disastrous consequences, for example doubling the likelihood of severe heat waves in Europe (Stott *et al.*, 2004). This has the potential to cause tens of thousands of premature deaths (Mitchell *et al.*, 2006). The change in global temperature enhances relative humidity by increasing the water content of the atmosphere. This in turn has the effect of further exacerbating the radiative warming of the planet. Observational evidence from oceans and continents show that regional climate change, in particular temperature increases, have been affecting many natural systems (IPCC, 2007d). There has been a change to snow, ice and frozen ground such that, for example, some ecosystems in the Arctic and Antarctic ecosystems have dramatically changed all the way up the food chain. The impact on ice cover has caused shifts in the range of algal and fish abundance in some oceans and caused earlier migration of fish in rivers (IPCC, 2007d). Terrestrial biological systems have also been affected by warming, with earlier occurrence of spring time events like egg-laying and bird migration. Table 2-1 details a selection of potential effects from the predicted increase in frequency of weather events and extremes throughout the 21st century (IPCC, 2007d).

Phenomenon and direction of trend	Examples of major projected impacts by sector			
	<i>Agriculture, forestry and ecosystems</i>	<i>Water resources</i>	<i>Human health</i>	<i>Industry, settlement and society</i>
Over most land areas, warmer and fewer cold days and nights, warmer and more frequent hot days and nights	Increased yields in colder environments; decreased yields in warmer environments; increased insect outbreaks.	Effects on water resources relying on snow melt; effects on some water supplies	Reduced human mortality from decreased cold exposure	Reduced energy demand for heating; increased demand for cooling; declining air quality in cities; reduced disruption to transport due to snow, ice; effects on winter tourism
Warm spells/heat waves. Frequency increases over most land area	Reduced yields in water regions due to heat stress increase danger of wildfire.	Increased water demand; water quality problems, e.g., algal blooms	Increased risk of heat-related mortality, especially for the elderly, chronically sick, very young and socially-isolated	Reduction in quality of life for people in warm areas without appropriate housing; impacts on the elderly, very young and poor.
Heavy precipitation events. Frequency increases over most areas	Damage to crops; soil erosion, inability to cultivate land due to water logging of soils	Adverse effects on quality of surface and groundwater; contamination of water supply; water scarcity may be relieved	Increased risk of deaths, injuries and infectious, respiratory and skin diseases	Disruption of settlements, commerce, transport and societies due to flooding; pressures on urban and rural infrastructures; loss of property
Area affected by drought increases	Land degradation; lower yields/crop damage and failure; increased livestock deaths' increased risk of wildfire	More widespread water stress	Increased risk of food and water shortage; increased risk of malnutrition; increased risk of water- and food-borne diseases	Water shortages for settlements, industry and societies; reduced hydropower generation potentials; potential for population migration
Intense tropical cyclone activity increases	Damage to crops; wind throw (uprooting) of trees; damage to coral reefs	Power outages causing disruption of public water supply	Increased risk of deaths, injuries, water- and food-borne diseases; post-traumatic stress disorders	Disruption by flood and high winds; withdrawal of risk coverage in vulnerable areas by private insurers, potential for population migrations, loss of property
Increased incidence of extreme high sea level (excludes tsunamis)	Salinisation of irrigation water, estuaries and freshwater systems	Decreased freshwater availability due to saltwater intrusion	Increased risk of deaths and injuries by drowning in floods; migration-related health effects	Costs of coastal protection versus costs of land-use relocation; potential for movement of populations and infrastructure; also see tropical cyclones above

Table 2-1: Examples of possible impacts of climate change due to changes in extreme weather and climate events, based on projections to the mid- to late 21st century

Source: IPCC (2007d)

It is clear that climate change is a huge threat to the world as we know it. Human activities have been blamed for global warming, and governments are starting to realise that action must be taken. So serious is this problem that it has been suggested that climate change issues could end up in the courts in the same way that war crimes and slavery have done in the past (Simms, 2005). There is therefore an ever increasing urgency to implement comprehensive mitigation and adaptation policies (Füssel, 2009).

The IPCC believe that current climate change mitigation policies and related sustainable development practices are not enough to slow the growth of global GHG emissions (IPCC, 2007b). They have published a set of scenarios that detail many different pathways towards change (Nakicenovic *et al.*, 2000) (see Chapter 5). It is commonly accepted that sustainable development can reduce the vulnerability to climate change but this development towards sustainable living may be hindered by climate change issues (IPCC, 2007d).

2.1.2 Global Equity for Sustainable Development

Climate change has been identified as a serious problem that must be dealt with globally. The release of GHG emissions must be reduced but balanced between the developing and industrialised worlds. Evidence has shown that much of the adverse effects of climate change will occur in the developing countries, for example, shifts in temperature and water supply will have serious consequences upon agricultural production, human health and settlements (IPCC, 2001). The developing countries are the least likely to easily adapt to climate change (Beg *et al.*, 2002), with economic growth and poverty reduction far higher up their agendas than climate change mitigation. Global equity is therefore necessary to allow those emerging economies the opportunity to grow and flourish. This gives rise to the need for sustainable development in combating climate change and humanity's overuse of the planet's resources.

2.2 DEFINING SUSTAINABLE DEVELOPMENT

According to Parkin (2000) there are some two hundred separate definitions of 'sustainable development'. The 2002 World Summit on Sustainable Development in Johannesburg adopted the strapline 'people, planet, prosperity' to reflect the requirement that sustainable development implies the balancing of economic and social development with environmental protection: the so-called 'Three Pillars'. The notion originally came to the fore as a result of the Brundtland Commission in the 1980s, which defined it in terms of the need to ensure "that development meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development, 1987). This implies that sustainable development depends not only on reducing ecological destruction but also on improving the material quality of life of the world's poor. In fact, developing sustainability may require a reduction in aggregate economic throughput, while enabling the poor to consume more. Others have argued, for example, that in order to

live in a sustainable world, society's demand on Nature should be in balance with Nature's capacity to meet that demand (Global Footprint Network, 2006d). This suggests that, to a large extent, development needs to be overshadowed by the 'environmental pillar'. An alternative approach stems from the work of Herman Daly, a well-known 'ecological economist', who defines 'growth' as an increase in economic size through material accretion, and 'development' as the realisation of fuller and greater potential (Daly, 1991). Consequently, in his terms, sustainable development aims at progressive social betterment without growing beyond the available biocapacity.

The Cambridge dictionary definition of 'sustain' is 'able to continue over a period of time'. This maintenance of our current situation is not accepted by many. It is argued that it is necessary to strive for continuous improvement for humanity as well as the condition of the planet's natural systems (Graedel & Klee, 2002). The concept of 'leaving the world better than you found it' is one which Graedel and Klee believe should be included in the definition of sustainability.

Parkin (2000) and Porritt (2000) have stressed that sustainable development is only a process or journey towards a destination, which is 'sustainability'. This end-game cannot easily be defined from a scientific perspective, but Graedel & Klee (2002) have attempted to establish a quantifiable, long-term target for sustainability from an industrial ecology perspective. They suggest a framework, or series of steps, to permit the establishment of the sustainable (or limiting) rate of natural resource use, which can then be contrasted with the current rate of consumption. The Graedel & Klee procedure requires the establishment of equal planetary shares of materials/emissions on a 50-year timescale. They acknowledge that the idea of an 'Earth share' or quota of this sort is controversial, and that the chosen timescale is somewhat arbitrary. Hammond (2006; 2007) has suggested that ecological footprints may provide an alternative quantitative indicator that might be able to better track humanity's pathway towards sustainability. Thus, such footprints indicate the degree to which biophysical limits have been approached or exceeded (Costanza, 2000). They are a partial measure of sustainability in the sense that they correlate well with the economic and environmental pillars, but not so with the social one (Hammond, 2006a; Hammond, 2007a).

2.2.1 Indicators of Sustainable Development

Progress towards sustainability can be assessed using various indicators. There are a variety of indicators for sustainability, and they should each be used as part of a toolbox of measures, since no one individual indicator can provide the full picture of sustainability that includes all 'Three Pillars' (UN, 2002): environment, economics and population.

One such indicator is the Human Development Index (HDI) which highlights the well-being of a country. HDI is a useful measure that combines indicators of life expectancy,

educational attainment and income into one singular index (UNDP, 2009b). Another indicator of sustainable development is the ecological footprint, which measures the demands placed on the biosphere (Chapter 3 details footprinting fundamentals). If biophysical limits are exceeded (using current technologies) then humanity is shown to be unsustainable. Thus, the ecological footprint identifies the degree to which biophysical limits have been approached or exceeded (Costanza, 2000). Ecological footprint analysis offers not only analysis of humanity's consumption of Nature's resources, but also shows where populations are profligate in terms of their overuse of natural capital, or more frugal (see Chapter 8). The ecological footprint has therefore been suggested as a helpful measure of sustainability (Houghton, 2009).

The ecological footprint is an excellent measure to aid countries in moving towards sustainable development by highlighting their resource use and consumption of Nature's reserves and comparing this to their available biocapacity (detailed explanation in Chapter 4). Not only does the footprint draw attention to overconsumption, but it also emphasises the inequality between nation states in terms of their ecological deficit or credit. This is vital to aid our understanding about the limited resources that are globally available to humanity.

The recent popularisation of the carbon footprint (see for example, Carbon Trust (2010), Directgov (2009) and Global Footprint Network (2009a)) focuses more significantly on the effects of GHGs, in particular carbon dioxide; this indicator can measure each person's, business's or even product's carbon emissions. Such measures stress excessive energy use or wasteful tendencies across different populations and are important so that mitigation and adaptation strategies can be implemented to avoid or moderate the impacts of climate change.

Concerns regarding climate change have been discussed in this chapter; the footprint is a useful aid to point governments and businesses to areas where improvements need to, and indeed can, be made. This enables countries to reduce their impact and contribution to global warming as well as decreasing their environmental and carbon footprint. As the effects of climate change become more severe, our available biocapacity will reduce, resources will become scarce and demands will increase with the predicted expansion in population. The footprint can offer a suitable measure to identify where these issues are arising and how humanity can adapt. Through analysis of the footprint real solutions can be identified for some of the most pressing ecological challenges in an equitable manner.

The ecological footprint is not the only indicator that is available to analyse environmental problems and the impacts of humanity upon the planet. Ecological indicators are frequently used to communicate information regarding the anthropogenic impacts upon the ecosphere, and to help inform decision makers. The

footprint has been adopted within this thesis due to its logical formation and since policy makers can readily understand the results and interpret them in a useful manner. The footprint is limited, in that it only considers resources that can be regenerated year to year and thus only accounts for effects upon the natural biosphere within this remit. There are many other factors that the footprint cannot indicate, such as the health and biodiversity of species or the well-being of human beings. Indicators such as the IUCN Red List of Threatened Species are far better placed to assess the problems relating to endangered species, or the UN Human Development Indicators that identifies the welfare of residents in particular nations. Indexes such as these are important and should be utilised within a basket of indicators to give a full and detailed assessment of the environmental impacts of humanity. The footprint was chosen for this work since the aim of the thesis was to compare the consumption differences between the populous South and the prosperous North. The key variables that were assessed include economic welfare and population; the footprint was the indicator best placed to make a detailed and coherent analysis of these varied, and often significantly different, factors.

There is a firm need for sustainable development in order to bring about change to prevent further climate change. Humanity is blamed for much of the damage caused by global warming due to the release of anthropogenic emissions. The catastrophic effects of climate change need to be mitigated and in order to achieve this, a movement towards sustainability is required.

2.3 SUMMARY

There are many different definitions of sustainable development, and it necessitates the not only the reduction of ecological destruction but also the improvement of the well-being of the world's residents. The ecological footprint is an indicator that is able to track and account for some of the actions of humanity and the impacts they have upon the biosphere. The footprint is applied throughout this thesis to compare and contrast the differences between the prosperous North and the populous South, in order to better understand the limited resources and inequity around the world.

2.4 THESIS FOCUS

The focus of this thesis is upon the use of the environmental and carbon footprint, highlighting key determinants and identifying the inequity between nation states, both historically and into the future as humanity attempts to follow the transition pathway to sustainability.

CHAPTER 3

STEPPING INTO THE FOOTPRINT

The basics behind the footprint and its formulation

3.1 BACKGROUND

The ecological footprint is an important indicator that measures human demand upon the global ecosphere and compares human consumption with Nature's ability to regenerate its natural capital. The footprint is a relatively new and popular indicator that illustrates the way in which resources are consumed and wastes produced by a defined community, business or product. Despite this, the concept is not new. Ideas of this type were first brought to prominence by Georg Borgstrom using the term 'ghost acreages' (Borgstrom, 1972); a measure of biocapacity [in hectares (ha)] - the capacity of a biologically productive area (land or aquatic ecosystem) to generate an on-going supply of renewable resources and to assimilate wastes. Around the same time, William Rees developed what he termed the 'regional capsule' (subsequently renamed as the 'ecological footprint') to teach planning students the importance of environmental accounting. Rees developed the idea from a planning point of view, and subsequently renamed the indicator of 'appropriated carrying capacity' as a footprint after purchasing a new desktop computer (Chambers *et al.*, 2000). Upon receiving the computer he was told it had a smaller footprint, in that it took up less space than his previous model. Wackernagel and Rees (1996) expanded these ideas to the far more detailed concept of the ecological footprint. The footprint concept was developed (Wackernagel & Rees, 1996) to help illustrate the burden that humanity places on the environment in absolute terms. Their work led to the now popular approach detailed in *Our Ecological Footprint* (1996). Despite it being a relatively recent formulation, it has been widely adopted in the context of education and awareness campaigns, as well as in the development of public policy (Simmons *et al.*, 2000).

The ecological footprint is defined (Wackernagel & Rees, 1996) as:

A resource accounting tool that measures how much biologically productive land and water area an individual, a city, a country, a region, or humanity uses to produce the resources it consumes and to absorb the waste it generates, using prevailing technology and resource management.

3.2 THE BASICS

Environmental or 'ecological' footprints are a simple, yet graphic measure of the resources consumed and the wastes produced by a given population with existing technology. The ecological footprint is used as a resource accounting tool that can often

address underlying sustainability questions (Global Footprint Network, 2006d). As well as being a simple measurement, it can be used to illustrate the extent to which humanity is using Nature's resources faster than they can regenerate.

The footprint of a nation is defined by the amount of land and water its population utilises; for food, materials, built-up areas, waste assimilation and the like. This varies considerably from country to country, and may be sustainable or unsupportable depending upon the availability of biocapacity, either globally or within the specified region. By taking a snapshot of our current ecological demands, footprint analysis can illustrate the burden that humanity places on the environment in absolute terms, as well as providing a useful benchmark to compare the success of alternative sustainable development strategies at global, regional, and national levels. Thus, ecological footprint analysis provides a useful, aggregate indicator of the environmental performance of nation states and other communities, as well as showing how far along the sustainable development pathway each has travelled. In order to hold countries to account for their impacts on the environment, their ecological footprint can be analysed.

Footprints are spatial indicators, measured in global hectares. Resources used and wastes produced by a population are converted to a common basis: the area of productive land and aquatic ecosystem sequestered (in hectares) from whatever source in global terms (Hammond, 2006a). Its main components are land directly built on: the fields, forests and mines employed at home and abroad to meet consumer demands, and the notional amount of land needed to absorb pollutants like carbon dioxide (Pearce, 2006). Thus the ecological footprint can be thought of as a measure of the 'load' imposed by a given population on Nature (Wackernagel & Rees, 1996). The determinants of these footprints have been correlated in terms of the economic wealth and population densities of countries from around the world (Cranston *et al.*, 2010; Hammond, 2006a) (see Chapter 8).

3.3 FORMULATING A FOOTPRINT

3.3.1 The Bubble Concept

The ecological footprint measures the land space necessary to provide for a specified population. Humanity has maintained use of resources outside the realms of settlements since the beginning of civilisation. Indeed most modern communities are far from self-sustaining, but exist by drawing upon the resources beyond their borders, bioregion or 'hinterland' (Doughty & Hammond, 2004; Rapport, 2000). Historically looking back as far as the hunter-gatherer tribes it is clear that humanity was dependent upon larger areas than the settlements themselves. Thus the space required to sustain populations has historically been far larger than the communities alone. The footprint draws upon this ideology, and can often be explained through the 'bubble concept'.

The 'bubble concept' is an illustration to demonstrate the basic ideas behind the ecological footprint. Using the city of London as an example, imagine a bubble is blown around the city boundaries to encompass all those businesses, people and networks within the borders. The area within this bubble is not large enough to provide the population and businesses of London with all their needs, such as food, clothing, waste assimilation and energy. Thus the bubble must be expanded to beyond the limitations of the city boundaries. The total area that this bubble must stretch to represents the total footprint necessary to support all those in the City of London maintaining the standard of living they are accustomed to. This increase in bubble size represents the imports and exports into a city, region or country. As such, footprint analysis is based upon the consumption patterns of a specified population, not its production.

Taking the idea of the 'bubble concept' it can be construed that all footprints must be trade corrected to account for the flows of goods and services in and out of specified countries or regions, such that:

$$\text{National Ecological footprint} = \text{Production footprint} + \text{Imports} - \text{Exports} \quad 3-1$$

where the imports and exports are also converted to a footprint equivalent basis. Applying this to the exportation of a product from the USA to a different country, say the UK, the resources and wastes associated with that product will be attributed to the British ecological footprint and not to the American one.

3.3.2 A Spatial Indicator

The footprint is a spatial indicator; it can be broken down into the productive land and sea space that support human demands for energy, food, fibre, timber and infrastructure. These areas are also allocated to absorb wastes from humans. The ecological footprint is spread across six different land use categories: cropland, grazing land, forest, built-up land, fishing grounds and land used for carbon sequestration. The breakdown of these land classes for the globe is shown in Figure 3-1. Each area is weighted according to their relative productivity and expressed in *global hectares* (Kitzes & Wackernagel, 2009) as discussed below.

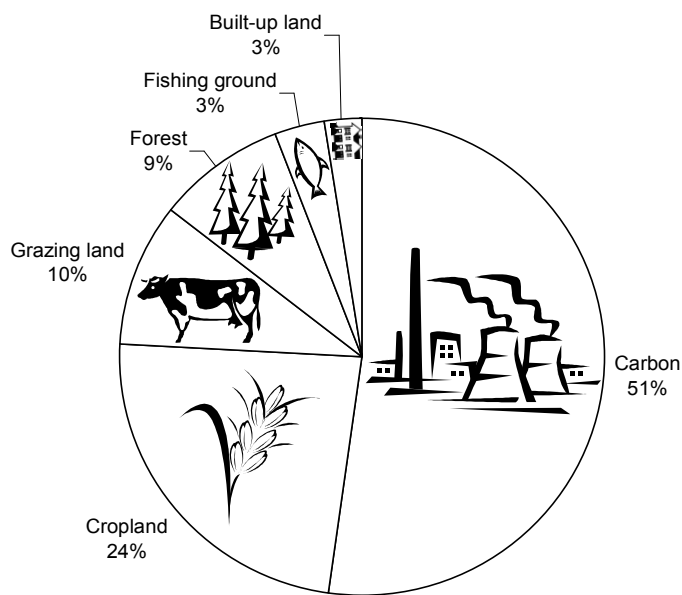


Figure 3-1: Breakdown of land categories for the World, 2005

Cropland represents the land space to grow crops for food, animal feed, fibre and oils. This land type has the highest bioproductivity per hectare of all the land categories. Animals that are reared for meat, milk, hides and wool may be fed from produce from cropland, or fishmeal from wild or farmed fish sources, or they may be allowed to range upon grazing land; often there is a combination. Fishing grounds represent the area necessary to sustain a harvested aquatic species; they are often located on continental shelves, which provide substantial sources of fish. Much of the deep sea area is excluded from the footprint since it is relatively unproductive. Forest area is used for the supply of timber, fibre and fuel, as well as the production of processed products such as paper and cardboard. Built-up land is necessary to account for infrastructure, including housing, transportation networks and industries. This land space is assumed to replace cropland since human settlers tend to reside in the most fertile areas. Carbon land is a slightly more complex category. The footprint accounts identify this region as the area of forest required to sequester carbon dioxide not absorbed into the oceans, given the current carbon absorption potential of world average forests (Kitzes *et al.*, 2007). Nuclear energy was originally included within this segment, but has subsequently been removed (see section 3.7.3).

The footprint can be broken down into these individual categories and represented graphically to highlight the dominance of each segment (Figure 3-2). The carbon uptake land embodies the majority of humanity's ecological footprint, and has increased the most since 1961 making a significant contribution to the overshoot that occurred in 1987, where the footprint became larger than the available world biocapacity (see Chapter 4). There have been relatively small amplifications in the other land type

categories, despite the growing population and subsequent increases in demands for food, living space and fuel. This is perhaps due to the improvements in technologies and efficiencies, but also highlights the unbalance in demand between the populous South and the prosperous North.

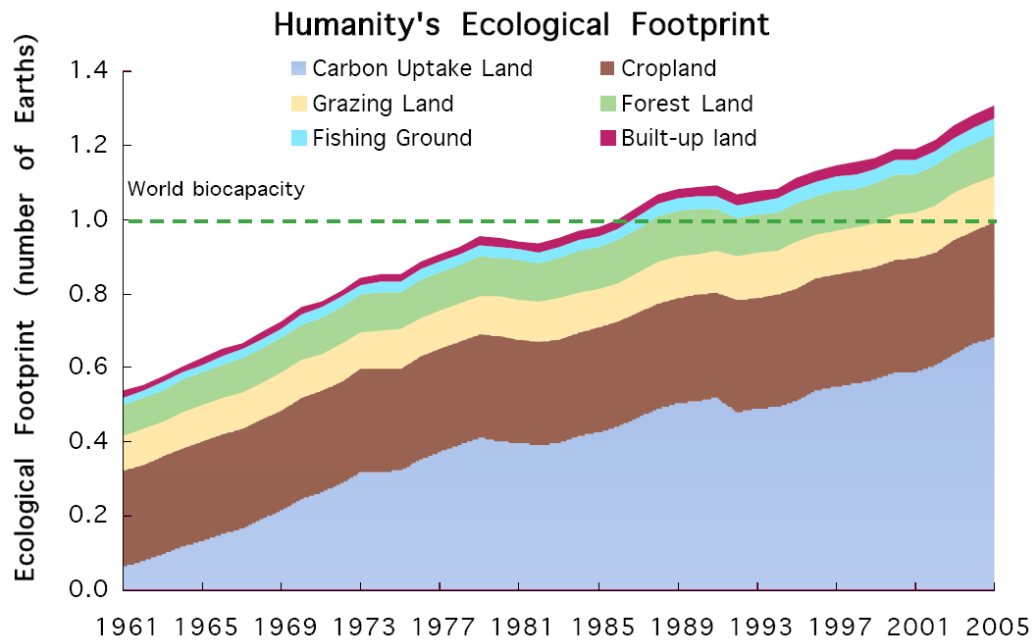


Figure 3-2: Humanity's ecological footprint by component

Source: Ewing et al. (2008a)

The average bioproductivity of land varies between land types and between different countries. The total footprint area is expressed as a standardised average biologically productive hectare of land (the *global hectare*), such that different populations and land areas may be comparable one with another. *Equivalence* and *yield* factors are used to convert different area types into the equivalent average biologically productive land in global terms, using the *global hectare* (gha). This average biological productivity, or 'bioproductivity', is normalised as having an equivalence factor of one. Countries will vary in the extent to which the bioproductivity for each category may be more or less productive when compared with the global average for the same type of land. Using equivalence factors enables account to be taken of varying bioproductivity of each land type. For example, cropland will have an above average bioproductivity with an equivalence factor greater than one. In contrast, grazing land is less productive, and will therefore have an equivalence factor less than one. Yield factors were developed to adjust each category in relation to the local yield and global standards.

3.3.2.1 Global Hectare

Using the global hectare enables direct comparison between nation states. A global hectare represents a standardised average productive hectare, such that one global hectare is equivalent to one hectare with productivity equal to the average productivity

of the available bioproductive land on Earth (Wackernagel *et al.*, 2006). A hectare of highly productive land is equal to more global hectares than a hectare of less productive land. Equivalence and yield factors are used to convert from hectares to global hectares, to ensure uniformity across differing regions.

There is in fact the same number of global hectares in the world as there are hectares. Hectares are simply converted to global hectares by weighting their productivity against the world average productivity.

3.3.2.2 *Equivalence factors*

An equivalence factor is constant for all countries in a given year. They represent the world's average potential productivity of a given bioproductive area relative to the world average potential productivity of all bioproductive areas (Wackernagel *et al.*, 2006). It is the difference between land-use categories, such that cropland is more productive than rangeland, with an equivalence factor of 2.64 gha/ha and 0.5 gha/ha respectively (see Table 3-1) (Ewing *et al.*, 2008b).

Area Type	Equivalence Factor (gha/ha)
Primary Cropland	2.64
Forest	1.33
Grazing Land	0.5
Marine	0.4
Inland Water	0.4
Built-up Land	2.64

Table 3-1: Equivalence Factors, 2005

Source: Ewing et al. (2008b)

3.3.2.3 *Yield factors*

Each country has a variety of yield factors, one for each type of bioproductive area. They describe the extent to which a biologically productive area in a given country is more (or less) productive than the global average of the same bioproductive area (Wackernagel *et al.*, 2006). For example the productivity of one hectare of pasture land may be more productive and thus able to support more meat production in New Zealand, than one hectare of pasture land in Algeria. New Zealand has higher productivity in pasture land than the world average (world average yield is 1), which is demonstrated by an equivalence factor of 2.5, whilst Algeria is below the world average with an equivalence factor of 0.7 (see Table 3-2) (Ewing *et al.*, 2008b).

	Cropland	Forest	Pasture Land	Fishing Ground
<i>World average yield</i>	1.0	1.0	1.0	1.0
Algeria	0.6	0.9	0.7	0.9
Guatemala	0.9	0.8	2.9	1.1
Hungary	1.5	2.1	1.9	0.0
Japan	1.7	1.1	2.2	0.8
Jordan	1.1	0.2	0.4	0.7
New Zealand	2.0	0.8	2.5	1.1
Zambia	0.5	0.2	1.5	0.0

Table 3-2: Sample Yield Factors for Selected Countries, 2005*Source: Ewing et al. (2008b)*

3.4 FUNDAMENTALS OF FOOTPRINTS

Ecological footprint analysis is based upon six assumptions. These assumptions ensure that there is a quantitative answer to how much regenerative capacity is required to maintain a given resource flow. The six assumptions for ecological footprint analysis (Wackernagel *et al.*, 2006) are:

- a) The annual amounts of resources consumed and wastes generated by countries are tracked by national and international organisations.
- b) The quantity of biological resources appropriated for human use is directly related to the amount of bioproductive land area necessary for regeneration and the assimilation of waste.
- c) By weighting each area in proportion to its usable biomass, the different areas can be expressed in terms of a standardised average productive hectare – the global hectare.
- d) The overall demand in global hectares can be aggregated by adding all mutually exclusive resource-providing and waste-assimilating areas required to support the demand. This means that none of the services or resources flows included in the Ecological footprint Accounts are provided on the same piece of land or sea space, ensuring that all areas are added only once to the ecological footprint. Otherwise double-counting would inflate the estimation of overall demand.
- e) Aggregate human demand (ecological footprint) and Nature's supply (biocapacity) can be directly compared to each other.

- f) Area demand can exceed area supply. This can be balanced through imports (ecological trade deficit) or the deficit is met by overuse of domestic resources, leading to a natural capital deficit (ecological overshoot) (see Chapter 4).

There are two fundamental techniques to calculate an ecological footprint. These are the compound and component methods (Simmons *et al.*, 2000; Wackernagel *et al.*, 2006). The component based model uses a bottom-up approach to derive footprint values, such that material flows are measured at a national or regional level. This method is therefore dependent on the accuracy and availability of material flows and the reliability of the LCA for each identified component. It is rare to find complete data records with a good history in the UK, let alone in other countries. Compound footprinting uses aggregate national data to establish ecological footprints; there is more complete data for this type of analysis.

‘Input-output’ modelling is often used for assessing footprints by researchers (see Turner *et al.* (2007) and Wiedmann *et al.* (2007) for example). This approach allocates the underlying components of the footprint into final consumption categories, using direct and indirect flows of money or physical products. This allows for the calculation of total footprint imports and exports, accounting for trade. The use of input-output frameworks can help to formulate a direct link between environmental consequences and economic activities (Kitzes *et al.*, 2008a), although it has been questioned whether it is appropriate to use monetary tables to assess land appropriation (Hubacek & Giljum, 2003).

3.5 NATIONAL FOOTPRINT ACCOUNTS

The Global Footprint Network produce National Footprint Accounts annually that aim to identify how much of the regenerative biological capacity of the planet is demanded by a given human activity (Kitzes & Wackernagel, 2009). This activity is fundamentally the consumption of a population, but could also detail the production of a particular good or provision of a certain service. These results can be compared to the biologically productive land and water space in order to assess the level of overshoot (Chapter 4).

The National Footprint Accounts are based upon calculations that primarily use international data sets from the Food and Agriculture Organisation of the United Nations (FAO), the International Energy Agency (IEA), the UN Statistics Division (UN Commodity Trade Statistics Database – UN Comtrade), and the Intergovernmental Panel on Climate Change (IPCC) (Kitzes *et al.*, 2007).

The ecological footprint for a country, in global hectares can be given by equation 3-2.

$$EF = \frac{P}{Y_N} \cdot Y_F \cdot EQF \quad 3-2$$

where P is amount of product harvested or waste emitted, Y_N is national average yield for that product P , and Y_F and EQF are the yield and equivalence factors described above (Ewing *et al.*, 2008b).

3.6 CARBON FOOTPRINT

The carbon footprint is the largest contributor to humanity's total ecological footprint¹, approximately 50% (Figure 3-1) (Ewing *et al.*, 2008b). The world's carbon footprint increased more than ten times from the 1961 to 2005 values, putting it at the largest demand on the biosphere from humanity (WWF International, 2008).

Carbon footprints are calculated by estimating the biologically productive area needed to sequester atmospheric CO_2 emissions through afforestation (IPCC, 2001) once absorption into the world's oceans is accounted for (equation 3-3). Carbon dioxide is absorbed into the oceans (approximately one-third) and removed from the atmosphere for prolonged time periods due to the burial of organic carbon in marine sediments.

$$EF_C = \frac{P_C \cdot (1 - S_{ocean}) \cdot EQF}{Y_C} \quad 3-3$$

where P_c is annual production emissions of carbon, S_{ocean} is the percentage of anthropogenic emissions absorbed by the oceans and Y_c is the annual rate of carbon uptake per hectare of world average forest land, and EQF is the equivalent factor for forests (Ewing *et al.*, 2008b).

Carbon dioxide has become very topical but it is not right to exclusively focus on it alone (Ayres, 2000) (see Chapter 9 for detailed discussion). However, Simms *et al.* (2010) have stated that since CO_2 produced by burning fossil fuels is (a) approximately 70% of all anthropogenically produced greenhouse gases, (b) has a long atmospheric lifetime and (c) is the best studied and modelled of the greenhouse gases, just focusing on CO_2 is a good starting point. There is a discussion regarding the use of CO_{2eq} or other additional GHGs within the carbon footprint (see section 3.7.2).

Carbon footprints have been focused upon in the media, however, an ecological footprint looks not only at the carbon emissions of a population but also takes into consideration water, food, renewable materials, built-up areas and waste assimilation, giving a far more holistic view.

¹ when looking at developing countries other contributions may dominate

3.7 PRAISE, LIMITATIONS AND CRITICISM

3.7.1 Ecological Footprinting Benefits

The footprint has been popularised in media over recent years, and seems to have captured the imagination of the general public in ways that other methods have failed to do so (Rees, 2000). The footprint is accepted as a useful resource that is easily communicable and has effective pedagogic uses since footprint analysis reduces all environmental impacts to a common basis in terms of global hectares *per capita*. It was originally noted by Costanza (2000) that the general public can readily understand land area as a numeraire and it is therefore a suitable heuristic indicator. It has the advantage of being an aggregate indicator, converting complex dynamics and resource use into one singular number. This offers benefits to leaders who need simple indexes to inform their decision making processes. The footprint is measured using a single, concrete variable – land area – to help consolidate all data collected into one simple value. This can be likened to traditional measures of economic welfare, such as the gross domestic product (GDP) or gross national income (GNI) (Hammond, 2000; Hammond, 2006a). However, with the simplicity of an individual number also comes the risk that only those well informed can interpret its true meaning, and others may remain ignorant of the complex issues, uncertainties and assumptions that are associated with it. It is agreed that in using the footprint, clear messages can be translated by policy makers as well as the general public (Moffatt, 2000). It has indeed been argued that the most important strength of the footprint is its conceptual simplicity and intuitive appeal (Rees, 2000). The footprint is able to cross disciplines, communicate the problems of consumption to the general public and inform about the overuse of the Earth's natural capital, such that it is able to translate the critical dimensions of human ecology to other disciplines and non-scientists alike. Indeed businesses and government leaders have adopted the footprint to assess their position and gradual transition towards sustainable development. It has even been suggested that ecological footprinting is the best method to make appropriate assessment of the extent to which consumption within a particular population is exceeding biocapacity (Ferguson, 2001).

Ecological footprint studies quantify the dependence of cities on their host ecosystems, underscore their vulnerability to global change, and highlight their role in achieving sustainability (Rees, 2000). Therefore as well as being a simple measurement, the footprint can be used to illustrate the extent to which humanity is using Nature's resources faster than they can regenerate. These footprints draw attention to the inequalities between nations in terms of burdens they place on the Earths' carrying capacity. Measuring the ecological footprint of a particular population – be it an individual, a city, a nation or all of humanity – provides a useful basis for contrasting the footprint of human activity with the available productive area or biocapacity (Chapter 4). The consequences of human consumption can then be graphically viewed against the natural capital of a community, nation, region, or the planet as a whole.

The ecological footprint aggregates and converts typically complex resource use patterns to a single number which is the equivalent land area required (Costanza, 2000). It can be argued that decision-makers are often too busy to deal with details and research behind these complex issues, so this aggregate indicator helps to simplify the decision making process. However, if one is not careful and well informed, it is possible to be ignorant of the source data, how they were aggregated, the uncertainties, weights and assumptions involved; thus a delicate balance must be struck.

Ecological footprint analysis is a 'static' process that provides a measure of aggregate environmental burdens for a specified date (or year) – a 'snapshot'. It is nevertheless a valuable technique in a toolkit of measures that can aid the assessment of sustainable development. It can be used as an effective awareness raising tool for illustrating human resource use and waste generation, employing a simple measure that is readily understandable. There are many implications for an ecological footprint in business, government and academia (see Chapter 4). Ecological footprint Analysis aims to give an idea of humanity's impact and advocates precaution (Wackernagel & Rees, 1996). Footprint analysis does not pretend to be an accurate model, but rather a reliable estimation of natural resource consumption and waste assimilation. With further research into the area, analysing the fundamentals of the technique and applying it to case studies, the ecological footprint may become an even more powerful and evermore useful tool.

3.7.2 Drawbacks of Footprinting

Despite large amounts of praise, others have widely disputed the benefits of the ecological footprint (Costanza, 2000; Ferguson, 2001; Fiala, 2008; Kitzes *et al.*, 2008a; Kitzes *et al.*, 2009; van Vuuren & Smeets, 2001). Moffatt (2000) has even argued that using Ecological footprint Analysis is nothing more than an attention grabbing tool.

The importance of using other indicators alongside the footprint must be emphasised; the footprint alone does not include a full range of sustainability issues, making it arguably weak in terms of social inequalities or poverty within and between different countries and societies. It is argued that footprints are too aggregated, and too limited in other respects, to be adequate for policy purposes (Ayres, 2000). The ecological footprint can be used to assess a nation's progress in terms of sustainable development, however, it should be considered as one available parameter in a toolbox of indicators since it does not consider, for example, the human effects of environmental degradation and resource poverty. Clearly ecological footprint analysis would need to be supplemented by the use of other measures to account for the broader elements of human welfare – the 'three pillars'. It is far more useful to achieve a more complete picture by using the footprint with other indicators, such as the UN Human Development Index (HDI) when assessing sustainable development of not only the ecological limits of the world, but also human needs and well-being (Moran *et al.*, 2008).

Ecological footprinting is not all inclusive and it is unlikely that the footprint will ever cope satisfactorily with the wide range of issues and factors effecting climate change. For example, carbon dioxide is the only anthropogenic emission that is fully implemented with the footprint analysis. It has been criticised that there is a lack of other greenhouse gas emissions within the footprinting methodology, identifying methane, sulphur and nitrogen as important emissions that all have ecological consequences but are not stipulated within the footprint (Ayres, 2000). The footprint is therefore limited in terms of its scope. By not including some of the additional factors that have been emphasised (Ayres, 2000; Rees, 2000) the footprint can often be seen as an underestimate, which highlights the need for immediate action to move out of overshoot and shift towards sustainable living. Wackernagel & Silverstein (2000) agree that the footprint does indeed contain some underestimates, but despite these sometimes crude estimates, the world has been shown to be in overshoot already.

The footprint does not contain the full range of humanity's demand on the biosphere. Even Rees (2000) argues that the footprint methodology is limited since it is not all inclusive. Many results therefore represent underestimates of the true implications and impacts of our lifestyles. This is in part due to the uncertainties within the data sets, but also because some activities involve the release of materials for which the biosphere has no significant assimilation capacity, for example plutonium, and processes that damage the planet's future biocapacity, such as soil erosion and loss of biodiversity (Kitzes *et al.*, 2007). However, the consequences of these activities are included within the footprinting accounts as a subsequent decrease in biocapacity.

Footprint analyses offer a snapshot of the current demands on natural capital. The technique does not account for the 'social pillar' of sustainable development, i.e., social inequalities or poverty between nation states and societies. Some have criticised the fact that ecological footprints are calculated on the basis of prevailing technology, for example Ayres (2000). Technological enthusiasts argue that technology fixes will be able to overcome biophysical constraints faced by humanity. Clearly innovation and technological development are key factors in driving economic growth. Given that footprinting only provides a static (one year at a time) analysis, it is difficult to take into account either underpinning technological changes or the adaptability of social systems.

The global and national footprint results reported in the WWF *Living Planet Reports* (2002, 2004, 2006, 2008) have been viewed by some (see the discussion in Hammond, 2006) as amounting to something of a 'doomsday' scenario in the tradition of Thomas Malthus' population projections in the 19th Century and the classic *Limits to Growth* study in 1970s. Criticisms have also been made concerning the dominant influence of fossil fuels in footprint calculations. It may underestimate the potential of a switch to renewable energy technologies in lowering the planetary footprint (Hammond, 2006).

Indeed ‘technological optimists’ typically argue that new technology will enable humanity to overcome biophysical limits (Costanza, 2000), thereby making development sustainable. McManus and Haughton (2006) have offered what they term a ‘sympathetic critique’ of both the theory and practice of ecological footprinting. They believe that, if poorly interpreted, it can mislead policy makers. Users should therefore be aware of its strengths and weaknesses; like those noted here. But even McManus and Haughton acknowledge that it has great “visual and commonsense appeal”.

It is true that the footprint analysis method is simple, but it is not likely that there will ever be a tool that is totally complete. It is a static analysis, so it is difficult to take into account technological changes or the adaptability of social systems, but prediction was never the intention. Instead, it is used to give an indication of the current situation.

There has been some criticism regarding the accuracy of primary source data in the National Footprint Accounts (Kitzes *et al.*, 2008a). Much of the data utilised by the Global Footprint Network are taken from international agencies such as the United Nations Food Organisation and the International Energy Agency, other sources are also used, including scientific papers and national databases. The quality of some datasets have been questioned (Kitzes *et al.*, 2008a), with particular reference to the reporting of fishing grounds in China, where many transactions are not officially documented, and thus bias the results significantly. Kitzes *et al.* (2008a) recommend that independent review of the data sets should be undertaken to ensure the acceptability of such sources.

3.7.2.1 Criticising the Carbon Footprint

The carbon sequestration method adopted by the National Footprinting Accounts (Global Footprint Network, 2006c) assumes that sequestration is dependent upon the ability of forests to absorb CO₂. It allows for global changes in forestry sequestration capabilities, as trees mature or young forests grow. The carbon footprint is currently calculated by establishing the amount of forest land required to sequester carbon dioxide emissions from fossil fuel combustion, using world average sequestration data for forest land and taking account of carbon uptake in the world’s oceans. This methodology has been disputed since the forests assumed to absorb the carbon emissions must be relatively young to fix large amounts of carbon. This implies that older forests can no longer provide this service, and would have to be preserved to be counted as a realistic carbon sink (Kitzes *et al.*, 2008a). Indeed, this implies that the mature forests which may be included within the energy land estimation cannot be included every year, but instead new land for young trees must be found to maintain the carbon sequestration levels required (Haberl *et al.*, 2001). Reforestation may physically cause problems with available land space. van den Bergh & Verbruggen (1999) highlighted that appropriate land will become more scarce as more land is reforested. A variety of alternative methods to calculate the carbon footprint have been considered, including equating the energy potential from burning fossil fuels to that of biofuels and hence converting the value of biofuels to global hectares or accounting for

all land types, not just forest land, needed to sequester anthropogenic carbon emissions (Kitzes *et al.*, 2008a).

As well as the debate surrounding the methodology of carbon sequestration, there is the issue that carbon dioxide has a residence time of around 100 years in the atmosphere, and that perhaps this should be accounted for in the footprint. The build-up of atmospheric CO₂ concentrations is largely as a result of emissions released by the developed North from the onset of their 'industrial revolution'. Although the developing world is expected to overtake the North in terms of gross levels of CO₂ emissions per annum, the industrialised countries are principally responsible for the build up of CO₂ concentrations in the atmosphere. Thus the industrialised world should take the lead in mitigating the global release of GHGs.

The debate surrounding the carbon footprint is developed in Chapter 9.

3.7.3 Developing Footprinting Methodology

The footprinting methodology has been developed considerably over the last decade, with improvements and changes implemented to better the scientific basis and accuracy of the models. There has been debate about the inclusion of nuclear power, the requirement of accounting for other GHGs such as methane and the way in which carbon dioxide emission sequestration is calculated.

Nuclear power was included within the National Footprint Accounts for the years 2002 to 2006 (WWF International, 2002; WWF International, 2004; WWF International, 2006); calculated as the amount of land that would be necessary to sequester the emissions of carbon dioxide if the same amount of electricity were generated using fossil fuel energy sources (Kitzes *et al.*, 2008a). The inclusion of nuclear power has subsequently been revoked for the 2008 edition of the accounts (WWF International, 2008). This was eliminated from the footprinting accounts as it was considered inconsistent with the methodology, and the use of fossil fuel equivalency did not reflect any real measurement of demand on the biosphere (Kitzes *et al.*, 2008a). Indeed, there was no proven scientific basis for assuming parity between fossil fuel use of electricity generation and the equivalent nuclear power production (WWF International, 2008). Other issues surrounding the problems such as waste storage, plant accidents and weapons proliferation could not be satisfactory dealt with either. Currently the footprint accounts include the emissions of true, direct carbon and land requirements that are associated with nuclear power, such as carbon sequestration land for carbon emissions and built land for infrastructure. The issue with removing nuclear power from the footprint was that those unfamiliar with the methodology may view this as a positive for the nuclear industry since it appears to have no effect on the biosphere (Kitzes *et al.*, 2008a), thus it could be interpreted that that the footprint accounts condone its use as a power generator. This underlines the importance of

communicating footprinting methodology to the general public and policy makers to prevent this type of misinterpretation.

The methodology behind the carbon footprint has been disputed, particularly with respect to sequestration of carbon dioxide by young trees which represent the best carbon sink (Wackernagel & Silverstein, 2000). Alternative methodological changes have been suggested, that include (a) using all bioproductive land not just forests to sequester CO₂, (b) converting the amount of biofuel that would produce the equivalent energy, and (c) using the value of original global hectares necessary to produce the quantity of fossil fuels (Kitzes *et al.*, 2008a). Each of these alternative methods has advantages and disadvantages. The first would give a far more detailed analysis of carbon uptake, and reflect more realistically the ability of the biosphere to sequester carbon. However, this method would necessitate set-aside land of different types to be permanently reserved. The second option is easily communicable, but further discussion surrounded the sustainability of biofuels is necessary. The final suggestion goes against footprinting fundamentals that focus only on present day demands; it also presents the problem of complex calculations to form a total aggregate value. Therefore, none of these options have been implemented to date.

The inclusion of other greenhouse gases has been suggested (Kitzes *et al.*, 2008a). These could be included in the footprint calculations by converting the global warming potentials of each gas to an equivalent carbon value. However, this is not consistent with the basics of footprinting since it is not possible to sequester these additional GHGs in the same way as CO₂. Emissions from land use change are also not currently included in the footprint. Although a large amount of CO₂ may be released (up to 30% of combusted fossil fuel emissions (Kitzes *et al.*, 2008a)) the methodology for accounting for these effects is unclear, particularly given that they will occur in the future.

3.8 SUMMARY

The footprint is a highly powerful and useful tool. It is a readily understandable and intuitive indicator that identifies humanity's use of the Earth's natural capital in terms of a spatial value – the global hectare. This indicator can be broken down into different land type categories, one of which has had a lot of media attention – the carbon footprint. The footprint accounts for the land and water its population uses, as well as the food, materials, built-up areas and waste assimilation. It is an aggregate indicator that can be used to identify the differing environmental performance, particularly in this thesis, of various nation states. The Global Footprint Network generates National Footprint Accounts annually that provide data for such analyses to be performed.

The footprint is not without fault and has been criticised, for example, for its inability to account for the full range of humanity's demand upon the biosphere since it doesn't include all GHGs or toxic wastes. The carbon footprint also receives criticism, which

includes debates around the carbon sequestration methodology (currently based upon the absorptive capacity of forests). Despite this critique, the footprint continues to be improved and developed, and is an important tool in assessing our impacts upon the planet.

The work within this thesis aims to develop understanding behind the both the carbon and ecological footprints. Relationships between these footprints and a host of variables are considered, culminating in final correlating 'power-law' equations. These give further insight into how the footprint can be translated and give more detail regarding the fundamental essence of these indicators.

CHAPTER 4

LIVING BEYOND OUR BIOPHYSICAL MEANS

Ecological Debt and Global Imbalance

4.1 INTRODUCTION

The distinguished systems ecologist Howard T. Odum, and his wife Elizabeth (see, for example, Odum and Odum (2006) and Hammond (2007a)), argued that the industrialised nations would have to descend from their current growth path. They suggested that civilisations rise, before their subsequent decline and fall; an idea taken from ‘Nature’s Pulsing Paradigm’. The Roman Empire in Europe (270 BC – AD 476) and the Mayan civilisation of Mesoamerica (AD 300-900) are classic examples. In the modern era, the decline would be marked by the end of the predominance of cheap oil; long predicted by King Hubbert and others (Hammond, 2007a). It is unlikely that humanity will ever again have access to concentrated energy sources of the nature of the fossil fuels: coal, natural gas, and oil. Resource scarcity and consequent rising costs will, according to the Odums (2006), induce the global economy to contract. Whether or not humanity will experience a collapse, or will be able to secure a sustainable future for people and wildlife, it is too soon to tell (Hammond, 2007a). Equity arguments will persist about whether burden sharing should be made on a *per capita* basis, on the available biocapacity of developed and developing regions, or account should be taken of their relative economic wealth. Nevertheless, both footprint analysis and systems ecology yield tools for coupling economy and ecology, along the lines advocated in the influential Brundtland report (World Commission on Environment and Development, 1987). They also provide a means for raising awareness of global sustainability issues amongst the wider populous.

This chapter provides an introduction and discussion regarding the use of ecological overshoot and the imbalance between nation states across the world, in order to set in context the debates surrounding the developments of the majority South and prosperous North.

4.2 MEASURING HUMANITY’S GREEDY DEMANDS

The ecological footprint represents resource demand; this reflects both the level of consumption and the efficiency with which resources are turned into consumption products. Biocapacity is the resource supply which varies each year with ecosystem management, agricultural practices, ecosystem degradation and weather (Global Footprint Network, 2005). The measure of the ecological footprint and its comparison

to the available biocapacity draws attention to the inequalities between nations in terms of burdens they place on the Earths' productivity.

Measuring the ecological footprint of a population, be it an individual, a city, a nation or all of humanity, allows the assessment of overshoot. In order to live, humanity consumes what is available to us from the planet. However, presently we consume above the levels that the Earth can renew. In 2004 humanity's footprint was over 23% larger than what the planet can regenerate (Global Footprint Network, 2006d); this means that it would actually take over one year and two months to regenerate what was used in that single year. In 2005, the global ecological footprint was 17.5 billion gha, or 2.7 gha per person, and the total biocapacity was 13.4 billion gha, or 2.1 gha per person (WWF International, 2008), clearly representing an overuse of natural capital. For the year 2006, humanity's footprint overshoot the Earth's capacity by over 40% (Global Footprint Network, 2010a), equivalent to a year and five months of re-growth to meet the demands for that single year. This overshoot is only possible due to the stocks of, for example, fossil fuels that humanity can access, much like an overdraft in a bank account; this credit cannot last forever.

4.2.1 Biocapacity

Footprints can be used to compare humanity's demand upon Nature's resources with the actual available resources, or *biocapacity*. Biological capacity, or biocapacity, is the capability of ecosystems to produce useful biological materials and to absorb wastes generated by humans using current management schemes and technologies (Kitzes *et al.*, 2007). Biocapacity is effectively the value of ecologically productive land available (Ferguson, 2002). In the same manner as for the ecological footprint (Chapter 2), biocapacity is expressed in terms of the global hectare. Biologically productive regions represent the area, both land and water, that support significant photosynthetic activity and biomass accumulation that can be utilised by humanity. It has been noted that the Earth's biosphere had around 11.2 billion hectares of biologically productive area, which is equivalent to a quarter of the Earth's surface (Kitzes *et al.*, 2007). This was broken down to 2.4 billion hectares of water, and 8.8 billion hectares of land (Figure 4-1). The land was made up of 1.5 billion hectares of cropland, 3.4 billion hectares of grazing land, 3.7 billion hectares of forest land, and 0.2 billion hectares of built-up land (Kitzes *et al.*, 2007).

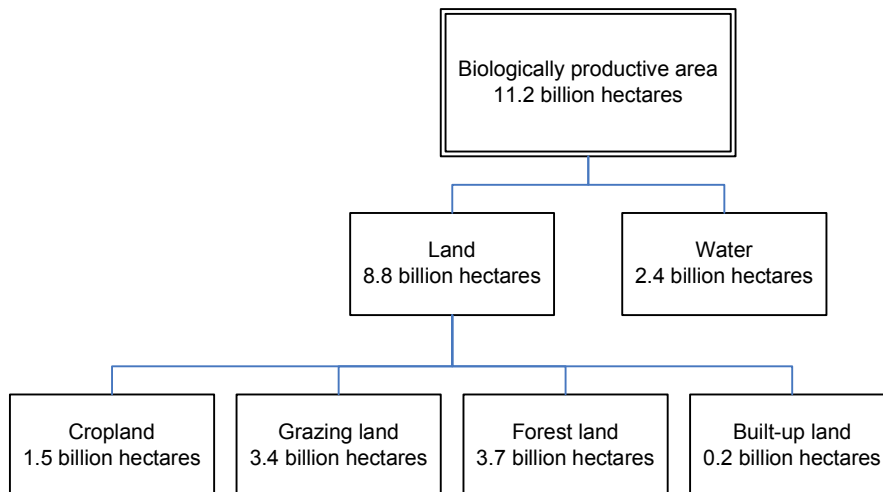


Figure 4-1: Breakdown of biologically productive area distribution

Biocapacity is the sum of bioproductive areas (in global hectares) for a specific nation. It is calculated by equation 4-1.

$$\text{Biocapacity (gha)} = \text{Area (ha)} \times \text{Equivalence Factor (gha/ha)} \times \text{Yield Factor} \quad 4-1$$

The per capita value of biocapacity is calculated by dividing the total biologically productive area by the population of the planet. This calculation does not account for any of the demands of other species.

4.3 OVERSHOOT – OUR EXPANDING ECOLOGICAL DEBT

The Earth has a certain value of ‘carrying capacity’, the natural resources available for consumption. When the size of a footprint is larger than this biocapacity, the biosphere is said to be in *overshoot* or *ecological debt*; this represents the unsustainability of a population and indicates an imbalance between regions. In 2006, humanity's ecological footprint grew by almost 2% from the previous year, and 22% from a decade earlier, due to a combination of rising population and per capita consumption (Global Footprint Network, 2009c). At the same time, biocapacity has not increased, and may even have fallen slightly. In fact, humanity's impact on the planet has more than tripled since 1961, so much so that the total footprint now far exceeds the regeneration capacity of the Earth. The population is living on resources (principally fossil fuels) laid down over geological timescales. Thus there is a stark difference between the average global per capita ecological footprint and the average available biocapacity per person worldwide, at 2.6 gha and 1.8 gha respectively (Global Footprint Network, 2009c). Thus, if global demand exceeds the globally available supply, there is a strong indication that natural capital is being liquidated – the state known as overshoot (Wackernagel *et al.*, 2004).

The ecological footprint documents humanity's demands on Nature. Humanity has been using resources faster than they can regenerate and creating waste such as CO₂ faster than it can be absorbed. Since the mid 1980s, humanity has been in ecological

overshoot with annual demand on resources exceeding what the Earth can regenerate each year (Global Footprint Network, 2006a; New Scientist, 2006) (Figure 4-2). Figure 4-2 shows that in 1961 humanity was using a little above half of available global biocapacity, but by 2006 ecological debt was huge, using 44% more of Nature's capital than was available (Global Footprint Network, 2010a). This illustrates how quickly global ecological deficit is growing, and humanity is becoming deeper and deeper in debt by demanding far more resources than is available in annual natural capital.

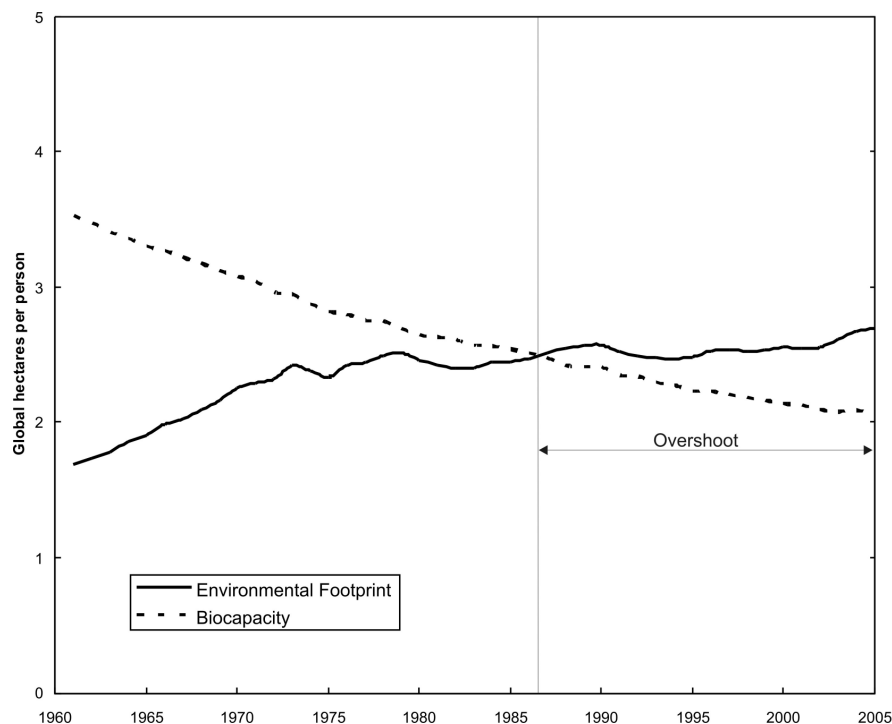


Figure 4-2: Human demand on the biosphere, 1961-2006

A country can survive by importing biocapacity from other nations, or by depleting its own ecological assets. It is possible to be in an overshoot situation in the short-term because humanity can liquidate its ecological capital (for example fossil fuels) faster than living off annual yields (Global Footprint Network, 2005). Ecological footprint analysis by no means implies that living at carrying capacity is a desirable target. Rather, the ecological footprint is intended to show how dangerously close we have come to Nature's limit (Wackernagel & Rees, 1996).

Overshoot may be undetected if governments and business leaders are not informed of how much of Nature's capacity we use or how resource use compares to existing stocks. Ecological limits can be hard to identify, and as such it is possible to be using stocks faster than they can replenish without realising; this is often the case for groundwater that is overused before the consequences are realised (Wackernagel *et al.*, 2004). This ignorance would lead to increasing the ecological deficit and reducing Nature's capacity to meet society's demands (Global Footprint Network, 2006d).

A population may be termed as being in *ecological debt* (Simms, 2005), or deficit, when its consumptive ecological footprint exceeds its own biocapacity (equation 4-2).

$$\text{Ecological deficit (gha)} = \text{Footprint (gha)} - \text{Biocapacity (gha)} \quad 4-2$$

It is possible for a country to be in ecological deficit if it is importing biocapacity from other nations (ecological trade deficit) or it is liquidating its natural capacity (ecological overshoot) (Monfreda *et al.*, 2004). These are defined by the following equations:

$$\text{Ecological trade deficit (gha)} = \text{Footprint}_{\text{imports}} \text{ (gha)} - \text{footprint}_{\text{exports}} \text{ (gha)} \quad 4-3$$

$$\text{Ecological overshoot (gha)} = \text{Footprint}_{\text{production}} \text{ (gha)} - \text{Biocapacity (gha)} \quad 4-4$$

Countries may continue running at an ecological deficit. They can use their own ecological assets faster than they regenerate each year, or they could be importing resources from other countries, and finally they could be generating more waste (such as carbon dioxide) than could be absorbed by the ecosystem within their own border.

The current economic climate (IMF, 2009) has illustrated what happens when debt and spending spirals out of control and this may happen with respect to our ecological debt (Simms, 2009). It is vital that we reduce our ecological debt before similarly disastrous consequences occur. Some impacts of our own ecological overspending can already be seen – climate change (Global Footprint Network, 2008a), world food shortages (World Bank, 2009), forest loss (WWF, 2009) and declines in biodiversity (UNEP, 2010) – all caused by our increasing demands that cannot be met by Nature. The sooner overshoot ends, the lower the risk of serious disruption and its associated costs.

4.4 GLOBAL UNBALANCE

Estimating the ecological footprint of a population – be it for a local community, a nation, or of the planet as a whole – illustrates the ecological impact that that population places on Nature. Ecological footprint analysis identifies the position of each nation as it moves along the pathway towards sustainable development. They draw attention to the inequalities between nation states in terms of burdens they place on the Earth's biosphere. In 2005 it was shown that half the global footprint was attributed to just ten nations; this demonstrates the disparity between the developing and industrialised world (WWF International, 2008). Although the industrialised world is currently responsible for a large part of worldwide emissions, as the developing world grows and industrialises it will significantly add to the damaging effects on the earth.

Since the beginning of the twentieth century the available *per capita* ecological space on Earth has decreased from between 5 and 6 hectares to only 1.5 hectares (Wackernagel & Rees, 1996). This coincides with an increase in the ecological footprints of people in

some industrialised countries, almost reaching 10 gha in some cases in 2005 (WWF International, 2008). These opposing trends illustrate the fundamental conflict confronting humanity and the real challenge of sustainability today.

Many high consumption regions are far from self-sustaining, and they only exist by drawing upon the resources from beyond their borders (Rapport, 2000). Industrialised countries (of the prosperous North – see Chapter 7 for definition) exhibit huge per capita ecological footprints, while the economically-disadvantaged nations (of the majority South – see Chapter 7) currently have relatively small ecological footprints. In essence, the ecological deficit in terms of carrying capacity of the Earth is much greater for the rich nations than for the poor. In fact, the rich nations can only sustain their lavish life-styles (relative to the rest of the world) by drawing down the natural capital of the poorer countries (Rapport, 2000). This is particularly negative, especially since 20% of human population enjoy unprecedented wealth whilst 20% earning less than 1.4% of the global income endure conditions of constant malnutrition (Wackernagel & Rees, 1996). A key element of sustainable development is therefore the need to focus on greatly improving the efficiency of resource use, and on reducing carbon (and other pollutant) emissions. Such actions would lower the ecological footprint of differing countries or regions of the world, and move humanity towards ‘sustainability’.

Ecological footprints highlight the disparity between nations in terms of the demands they place on the globe. Some countries' level of ecological demand per person is much higher than the world average and much lower for others. For example, the United Arab Emirates has the largest ecological footprint per capita, 9.5 gha, the average American has a footprint of 9.2 gha, whilst a European has a footprint of half that at 4.7 gha (WWF International, 2008). These values are far above the world average and exceed what is nominally available per person. Countries such as Malawi, Haiti, and Bangladesh, offer a complete contrast (Global Footprint Network, 2009c). They have footprints of about 0.5 gha, which is barely enough and in many cases is simply not enough, to provide basic needs such as food and shelter (Global Footprint Network, 2009c). It has been shown that between 1975 and 2003 wealthy nations improved their apparent ‘quality of life’ by increasing their resource use (WWF International, 2006). Over this same time period, developing countries, notably China and India, grew significantly but without altering their ecological footprint greatly. It is thought that as national ecological debt grows, there may be a shift in the geopolitical line (WWF International, 2006); instead of having a division between the developing world; the line would fall between ecological debtors and ecological creditors. Nations which have resources may preserve them solely for their own use, preventing others from having access to them. Less fortunate nations may prevent access to food, clean water or energy. The USA currently necessitates 23% of global biocapacity; with China requiring 21% despite its far lower per capita footprint but having a population quadruple the size of the USA. Due to this growing population, China’s resource use is expected to

rise much faster than the USA's, although on a per capita basis Americans will still have larger footprints (Global Footprint Network, 2009c).

Countries in ecological credit include those which are able to display an ecological under-shoot due to their sparsely populated territories – for example, Brazil, Canada and Russia. Many of the other countries in ecological credit are those poor developing countries in Africa, Asia, and Latin America (see, for example, Hammond (2006a)). Ecological creditors may have many ecological reserves; however, this does not necessarily mean that these assets are well managed, for they could be subject to overharvesting. There is evidently a long-term need to bring the Earth's ecological footprint back into balance with its biocapacity.

The problem of global unbalance can be summarised by the WCED (World Commission on Environment and Development, 1987):

“The Earth is one but the world is not. We all depend on one biosphere for sustaining our lives. Yet each community, each country, strives for survival and prosperity with little regard for its impacts on others. Some consume the Earth's resources at a rate that would leave little for future generations. Others, many more in number, consume far too little and live with the prospects of hunger, squalor, disease and early death.”

Strategies have been put in place, such as the Kyoto Protocol, to ensure emissions are limited and nation states work together towards the global goal of carbon reduction. The prosperous North must lead the way along this transitional pathway and encourage the majority South to follow.

4.5 FIVE FACTORS OF CHANGE

Eliminating overshoot and ecological deficit means shrinking the gap between humanity's ecological footprint and the Earth's biocapacity. This requires reductions in our demands on the planet as well as increasing bioproductive land space in a sustainable way. Lowering global ecological debt can be achieved through reducing consumption of biophysical assets with the ultimate goal of living within the biocapacity of one planet. To succeed in this shrinking and eventually eliminating debt, policies and practice must be attractive to people of divergent cultural backgrounds, living in different parts of the world. Regional ecological footprints vary significantly, and it may not be ethically sound to enforce a reduction in demand from all nation states of the World; many regions of the World must be allowed to grow to meet the aspiration to improve the well-being of its peoples.

In order to move out of ecological overshoot and decrease the global deficit of natural capital, the gap between ecological footprint and biocapacity must be reduced. Increasing ecosystem productivity may help, but it is the reduction of humanity's global

footprint that is essential (WWF International, 2006). The decrease in footprint and increase in biocapacity can be achieved through the five factors of change (WWF International, 2006).

4.5.1 Reducing the Ecological footprint

4.5.1.1 Population growth

Population growth can be decelerated and eventually reversed by encouraging families in a respectful and equitable manner to have fewer children. This can be achieved by, for example, providing women with better health care, education and economic opportunities.

4.5.1.2 Per capita consumption

Reducing consumption is partly reliant upon individual's economic welfare. Those affluent populations can afford to reduce their consumption whilst still improving quality of life, whereas those living at or below the poverty line need to increase their consumption to move towards acceptable standards of living.

4.5.1.3 Resource use

Significant reductions in resource use can be made in the production of goods and services. This may take a variety of forms, ranging from minimising waste and increasing recycling, to improving energy efficiencies in manufacturing processes, to reducing food miles or distances products are transported. Governmental and consumer pressure promote businesses to develop technical innovation and resource efficiency.

4.5.2 Maximising Biocapacity

Biocapacity is necessary to provide natural capital for humanity; as such increasing biocapacity enhances the planet's capacity to support global life systems. Biocapacity must be preserved, by protecting soil from erosion and other forms of degradation by safeguarding river basins, wetlands, and watersheds to secure freshwater supplies, and maintaining healthy forests and fisheries (WWF International, 2004). Yields can be maintained by mitigating the effects of climate change, and eradicating the use of dangerous chemicals that impact ecosystems.

4.5.2.1 Bioproductive space

Bioproductive area can be enhanced; for example through careful management degraded land can be reclaimed. Good land management must ensure that bioproductive areas do not diminish, being lost, for example, to urbanisation, salinisation, or desertification (WWF International, 2006).

4.5.2.2 *Bioproductivity per hectare*

Bioproductivity of any area is dependent upon how it is managed and the specific type of ecosystem. Care must be taken when utilising agricultural technologies as they can improve productivity but have a negative impact upon diversity (WWF International, 2006). Often yields can be boosted through the use of intensive agricultural techniques and fertilisers, but this comes with the disadvantage of higher footprints and increased inputs.

4.6 TRANSITION TO A SUSTAINABLE SOCIETY

‘One Planet Living’ or sustainable society is the critical result in reducing ecological debt. In order to achieve this there are a variety of steps, both slow and fast, that can be undertaken. It is necessary to accurately assess current situations, and innovate towards new ideas and solutions in order that humanity may move along the sustainability pathway.

Resource accounting is vital to assess our ecological deficits and overshoot (WWF International, 2004). Without accurately measured information it is impossible to see the effects of overshoot and where ecological bankruptcy must be avoided. Such measurements are designed to protect ecological assets and help to prevent and mitigate environmental crises and their socioeconomic consequences. Without accurate resource accounting used to highlight the effects of overshoot, it may become too late to change course and avoid ecological bankruptcy. The collapse of fisheries off the east coast of Canada (see for example Greenpeace (1997)) and the severe effects of deforestation in Haiti (see for example, Dolisca *et al.* (2007) and Than (2010)), are two unfortunate examples. Relevant information can be used to set baselines and developed to analyse the success or failure of sustainability strategies.

Innovative approaches to meeting human needs are called for if we are to move beyond the belief that greater well-being necessarily entails more consumption, especially in societies where basic needs are already being met. Effective sustainability strategies invite participation and stimulate human ingenuity. Systems thinking can help to identify synergies and ensure that proposed solutions bring about an overall footprint reduction, rather than simply shifting demand from one ecosystem to another (WWF International, 2004).

4.6.1 Tiers of Action

It is important that inter-connectivity is taken into account when trying to reduce the ecological footprint. Reductions can be made in one area, but this may inadvertently increase the footprint in another.

In the past, the most politically acceptable way of minimising the ecological footprint has been to improve the efficiency of production systems that convert energy and

resources into goods and services (WWF International, 2004). Technological advancement has been able to help compensate for much of the increases in per capita consumption over the last 40 years; it has maintained a relatively constant average per capita ecological footprint. These gains in efficiency are important and offer good prospects for improvements; however, on their own they are not enough to reverse the current trend in the overall growth of the Ecological footprint. Alternative and additional changes that have been suggested by the WWF (WWF International, 2004) include:

- a) Improving information for decision making
- b) Advancing product design and urban infrastructure
- c) Using markets and regulation
- d) Enhancing international cooperation

The responsibility of reducing ecological overshoot lies with all of humanity. Individuals, businesses, governments and the world wide population must all make a commitment to strive towards a sustainable future. This can be achieved through many levels of change and advancement. There is a need for long term changes in fundamental behavioural patterns, with the support of organisational and institutional backing and technological development. For example, a shift to higher use of public transport is only possible when technology advances and grows alongside peoples changing preferences and behaviours. Action can be taken at many different levels, be it individuals who choose to recycle, corporations improving their energy efficiencies or governments setting policies and financial incentives to encourage markets towards long-term sustainability strategies. Through the development of technology, education of peoples to enable behavioural shifts, and political support influencing systemic change, each person, company, government and region have the ability to transform humanity out of overshoot and towards one planet living (WWF International, 2004). Each tier of action can sum together to achieve our goal in ending overshoot.

4.6.2 Case studies for potential reductions

The ecological footprint has an important use as an awareness making tool, and also highlights where improvements can be made, where changes have been implemented and reductions achieved. They can be used as targets, ranging from global, to corporate, to individual goals if they are to be truly useful (Graedel & Klee, 2002). Many studies have been undertaken to assess the ecological footprint of cities and regions (Barrett *et al.*, 2002; Collins and Flynn, 2005; Global Footprint Network, 2007; Kitzes and Goldfinger, 2007; Stewart *et al.*, 2003), businesses (GTZ, 2010; Syngenta, 2010; Wackernagel and Stewart, 2005) and indeed countries (Global Footprint Network, 2008b; Niazi *et al.*, 2008; Ravetz, 2007). It is important to know that there are changes that can be made, and that have been undertaken by governments, businesses and individuals to make inroads in reducing overshoot. Some examples of how this can be

achieved and the reductions possible are highlighted below for cities, countries and business.

Marin County, California, has a per capita ecological footprint (27 global acres) that is slightly higher than that of the average American person (24 global acres). By calling for county-wide programs to encourage both individual and collective footprint savings, Marin's Countywide Plan exemplifies the type of actions that will be necessary to reduce global overshoot and achieve a prosperous and ecologically sustainable future (Kitzes and Goldfinger, 2007). Energy use in buildings was identified as representing a quarter of the total footprint, much of this coming from electricity. Marin can decrease its energy footprint through conservation and efficiency as well as by using renewable sources of electricity. Indeed, Marin County has set the target to increase renewably sourced energy to 25% by the year 2010, and to 40% by the year 2015 (Kitzes and Goldfinger, 2007). Biocapacity is also an important issue and must be protected. Marin aims to preserve its biocapacity by slowing activities that negatively impact ecosystem productivity. Marin County hopes to preserve 24,000 acres of land as open space, and 33,000 acres of agricultural land in easements (Kitzes and Goldfinger, 2007). Biocapacity can be found in smaller spaces, and Marin aims to increase local biocapacity by encouraging community gardens and small-scale green spaces.

Calgary is an excellent example of residents with very high per capita footprint, between 9.5 and 9.9 gha (Global Footprint Network, 2007). This exceeds the Canadian average of 7.6 gha per person and far beyond the world average of 1.8 gha per person. Steps are being made to reduce these values, and the footprint is being used to improve awareness of this excessive use of natural capital. An interactive personal calculator developed in partnership with the Global Footprint Network has been completed and is posted on the City's website (The City of Calgary, 2009); this encourages individuals to assess their consumption and adjust their habits to enable them to reduce their personal footprint. In this way a change in attitudes and lifestyle can be made from the bottom up, by using the footprint to illustrate consumer patterns.

As well as individual towns and regions, entire nations can be investigated and improvements suggested through the use of the ecological footprint. For example India is often mooted as being a fast growing and rapidly industrialising country with poor emission quality. Buildings in India are of considerable importance; construction is growing at nearly twice the global rate, approximately 9.5% (Global Footprint Network, 2008b). It is therefore vital that green design is adopted to promote sustainable practices and materials. More than 300 green building projects have already been undertaken which represents 230 million square feet of space and uses construction practices that are less resource-intensive (Global Footprint Network, 2008b). The Indian motor industry has an opportunity to redefine the market space through the use of new materials, new construction principles, and other ways to boost vehicles' fuel

economy by a factor of four or more over today's best practices (Global Footprint Network, 2008b).

In March 2001, the Welsh Assembly Government adopted the Ecological Footprint as their headline indicator for sustainability, making Wales the first nation to do so. Many reports have been written regarding the Welsh Footprint, and the most recent gives strategic recommendations for reductions up to 2050 (Ravetz, 2007). Examples include improving house energy efficiency by utilising new technologies and encouraging housing stocks to meet best standard practice. By engaging with every tier in the housing market, from residents to landlords, designers to builders, a reduction of 30% in the ecological footprint of buildings could be achieved by 2050 (Ravetz, 2007). Another example is the automotive industry: improvements in life-cycle design and the use of alternative fuels could see a 20% saving in the sectors footprint by 2050 (Ravetz, 2007).

4.7 SUMMARY

The ecological footprint is a far-reaching tool that has already been adopted by businesses and governments alike throughout the world. Its ability to raise awareness of humanity's overconsumption allows world leaders to become better informed about the effects their decision have on the World.

Biocapacity represents the capability of ecosystems to produce materials and absorb wastes that are generated by humanity. This offers a baseline from which to compare the ecological footprint. It is also measured in global hectares. When a population within a nation state has a *per capita* ecological footprint larger than the available *per capita* biocapacity, it is said to be in a state of ecological debt; that is the population is requesting more from nature's resources in one year than can be regenerated in the same time period.

Ecological debt is a serious problem, and one that cannot continue indefinitely without a crash. There is a huge global unbalance where many economically rich countries are drawing from the economically poor nations that are resource rich, this leaves little biocapacity for these nations themselves to theoretically use. The burdens upon the Earth are therefore growing. There is potential to make ecological savings and countries must be encouraged to move out of ecological debt and provide future generations with a more sustainable world. This must be pursued in an equitable and fair manner between the diverse nation states throughout the planet.

CHAPTER 5

SCENARIOS

'Like the real life from which they are drawn, the scenarios are mixed bags, at once wonderfully dreadful and dreadfully wonderful'

(Wilkinson, 2009)

5.1 INTRODUCTION

The future is uncertain; it is difficult to know what challenges, developments and changes lie ahead. In everyday life people make decisions based on the potential outcomes of their actions, be it making an investment, having children or something as simple as a weekly supermarket shop. These tend to be relatively short-term choices of small consequence. World leaders, on the other hand, regularly make important, far-reaching decisions that have significant effects not only upon humanity but also on the Earth for today and well into the future. The future is highly uncertain and these leaders need tools that can enable them to make decisions in the midst of so many unknowns; scenario formulation is one such tool. Scenarios are regularly used in relation to climate change and sustainable development to highlight different pathways into the future following a variety of energy use strategies, population growth and economic development, and help engage leaders with the problem of overshoot.

It is very hard to imagine what the future may be like in a hundred years time. The world has changed considerably in the last one hundred years, what with the development of aviation, space exploration, computer information technology and the World Wide Web. Many of these things would have appeared completely alien and abstract at the start of the 20th century. This makes it very difficult to try and comprehend, and indeed estimate, what advances may occur in technology and how the World's demographic and energy use, for example, may have altered by the end of the 21st century. It is not only challenging to imagine a future world, due to scientific unknowns and uncertainties, but just to think in such a long time-span is complicated. As well as technological changes, there will likely be a shift in geo-political powers, and alterations in societal beliefs and behaviours.

There are many gaps in historical data, making it difficult to assess past trends, thus scenarios are an excellent tool to interrogate the future, where changes in economics, technology, society and demographics can be integrated and assessed. This in turn encourages analysis of future climate changes, mitigation strategies and adaption policies to prevent impacts and situations of extreme vulnerability.

Scenarios are vital to the ongoing, global assessment of climate change. They allow for an engagement with different future developments in systems that are both complex and inherently unpredictable as well as having many associated uncertainties. They can be used to illustrate a variety of possible climate changes resulting from different demographic patterns, economic developments and environmental concerns. This enables policy and decision makers to be better informed and have a good basis from which to assess adaption strategies, mitigation to adverse effects, and prevention mechanisms as well as how best to implement appropriate policies.

Scenarios are not predictions or forecasts; they simply represent a variety of future alternatives. They are not intended to illustrate preferable developments or undesirable progressions, but instead describe a host of plausible futures. They can be used to further understanding about how systems evolve, develop, behave and interact. This is often useful for scientists where complex systems must be modelled and the behaviour within such systems further analysed. Policy makers can use scenarios to better appreciate the effects of climate change, and gain insight into different adaption, mitigation and impacts that may occur.

Scenarios have been adopted in this thesis to enable analysis of future footprints for the prosperous North and the majority South (see Chapter 10). The different carbon contributions from population and economic growth have also been considered historically and into the future through the use of scenarios (see Chapter 11). Scenarios from the IPCC's *Special Report on Emissions Scenarios* were implemented (see below).

The development and use of scenarios is examined within this chapter in order to determine the appropriate use of scenarios in the analyses detailed in Chapter 10 and Chapter 11; this is important to fulfil objective 4.

5.2 SCENARIO STUDIES

There is a vast range of scenario literature covering narrative descriptions, quantitative scenarios, and detailed models (Cranston & Hammond, 2010b). Scenarios are used frequently in the private sector, and the focus of the IPCC studies has been on greenhouse gas (GHG) emissions, principally carbon dioxide (CO₂) (Nakicenovic *et al.*, 2000). This enables the study of future energy and related industrial developments, and the way in which the resulting GHG emissions may impact on climate change over a given period. Considerable uncertainty surrounds climate change, particularly the interaction and long term impacts of anthropogenic emissions within the atmosphere.

The task of anticipating future developments is difficult especially when considering an extremely long time period. Nevertheless, long-term scenarios have been developed for the 'visioning' of global energy trends and strategies in the context of climate change science. Scenarios facilitate an analysis of the way in which future global developments

will influence the concentration of GHGs in the atmosphere, and their possible impact on climate change. Scenarios of the latter type fall into two categories: those that consider the uncertainties in the drivers for emissions (such as population, economic wealth and technology), or those that analyse uncertainty in the levels of commitment and effectiveness of global efforts to reduce climate change.

The first global sustainability study using scenarios was undertaken by the IIASA (International Institute for Applied Systems and Analysis), detailed in their book *Energy in a Finite World* (Hafele, 1981). The World was understood to be dynamic, with a growing population, changing economies and aspirations to achieve suitable development and growth to realise reasonable living standards. The focus was upon energy use and the required energy levels necessary to accomplish development, particularly within the Southern hemisphere. In a similar fashion to the IPCC, (Nakicenovic *et al.*, 2000) (see Section 5.4) assumptions excluded political constraints and was limited to more realistic scenarios with no ‘surprises’ or catastrophes included within the data sets. A 50 year timescale was chosen based upon twice the lifetime of powerplants, lead times for new technologies and two generations of humanity, therefore encompassing major changes whilst being within the limitations of realistic projections.

Since the recent rise in interest concerning climate change and a consciousness of humanity’s impacts on the Earth, many more scenarios have been explored not just by academic institutions, but also by businesses and governments. The World Business Council for Sustainable Development (WBCSD) has investigated the future within their Vision 2050 project (WBCSD, 2010). This details a pathway leading to a sustainable world in 2050, through changes in economic structures, governance, business and fundamental human behaviour, resulting in humanity living well and with the limitations of the planet. As such scenarios can be used to advise and steer decision makers, governments and world leaders towards understanding the consequences of their policies and decisions to give the best outcomes for humanity as well as the World. The World Energy Council (WEC) also assesses scenarios for carbon emissions and energy use. Most recently, the report *Energy Policy Scenarios to 2050* (WEC, 2007) builds upon earlier work (WEC, 1993), utilising recent updates to account for new estimates regarding population, technological development and climate change. These scenarios tend to be based upon the engagement of governments across different regions of the world, the different energy sector changes and the subsequent challenges that arise. The Global Footprint Network have also undertaken scenario analysis making suggestions as to future ecological debt, following a business as usual trend, slow shift scenario and rapid reduction assumptions (WWF International, 2006), as well as a possible ‘return to sustainability’ pathway (WWF International, 2008).

The IPCC have been developing scenarios since 1990, their IS92 report offered emission trajectories up to 2100. These were considered to be path-breaking since they included a host of GHG and SO₂ emissions. However, a number of weaknesses were identified, such as the limited range of carbon dioxide intensities and the continuation of the income gap between developing and developed countries with no convergence into the future. The scenarios were updated following this critique with a better understanding of climate change and its appropriate determinants, resulting in the *Special Report on Emissions Scenarios* (SRES) (Nakicenovic *et al.*, 2000). These scenarios have been readily adopted within academic circles and businesses alike due to the diversity of projections, the level of detail and scrutiny the report has undergone and the international recognition of the IPCC as a world leading group with the capacity and capability to develop scientifically acceptable arguments.

5.3 THE IPCC AND SCENARIOS

The IPCC is the leading body tasked with providing scientific analysis regarding climate change and possible environmental and socio-economic consequences, established in 1988 by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO). Many thousands of scientists voluntarily contributed to the review and assessment of climate change to further the understanding of this phenomenon. Through its strong scientific and intergovernmental standing the IPCC is able to provide balanced and rigorous information to decision makers.

The IPCC have previously developed a set of scenarios in 1990 and 1992; SA90 and IS92 respectively. There was much praise for these scenarios due to the excellent coverage of all the GHG emissions. However, there were a number of weaknesses associated with the scenarios. For example, Parikh (1992) highlighted the lack of closure between developing and industrialised countries in terms of their income by the end of the 100 year timescale. The developing world was also considered to be poorly represented in the modelling groups, and more of an effort should be made to engage experts from these regions in the next IPCC scenario development. The SRES attempted to improve upon the drawbacks of the IS92 scenario set and make advances by using more up-to-date techniques and models. They showed excellent results since they contained more recent driving force data, and were constructed in a fundamentally different way to the IS92 (Arnell *et al.*, 2004).

The IPCC developed a varied selection of different scenarios (Nakicenovic *et al.*, 2000). These are not predictions or forecasts, but are a suggestion of alternative futures. They were formulated using a set of reproducible assumptions based upon historical trends, relationships, and driving forces. Such scenarios range in complexity from baseline 'storylines' and consider a variety of plausible options. Thus a selection of future

emission paths from low to high can be assessed with respect to future response policies (Nakicenovic, 2000).

The IPCC formulated a set of emissions scenarios to describe a variety of future developments that could influence GHG emissions. Different driving forces were considered, covering a range from demographic to economic and technological developments (see Chapter 6). Of course there is a large uncertainty associated with scenarios, and it was for this reason that up to 40 scenarios were developed by the IPCC (Nakicenovic *et al.*, 2000), all considered of equal importance and probability. The final set of 40 scenarios were based upon careful literature reviews, six modelling approaches and underwent a detailed 'open process' whereby participation and feedback was collected from groups and individuals across the world. A time span of 100 years was selected for the scenarios in order that long term policy could be developed, rather than a focus on the short- and medium-term effects. Climate modellers also needed a large range due to the long response time of the climate system.

5.4 INTRODUCTION TO SRES SCENARIOS

The IPCC published the *Special Report on Emissions Scenarios* in 2000, also known as the SRES. 'Storylines' were developed as the starting point for the scenarios; these were narrative descriptions of how global populations, economies and political structures may develop up to 2100. In total four storylines were defined, and within each storyline was a group of scenarios, known as a 'family'. Six scenarios were selected to best represent each storyline (one family had three marker scenarios based on different energy strategies) and these were called the 'marker' scenarios. The storylines were used by climate modellers to develop a set of comprehensive, comparable climate scenarios. As such the qualitative storylines were translated into quantitative and scientifically acceptable models.

The SRES scenarios were based on an extensive literature assessment, six different modelling approaches and an 'open process' that engaged many individuals and groups in active participation and feedback. The IPCC ensured that all of their scenarios were internally consistent and were reproducible through a set of assumptions regarding the relationships between the driving forces (Nakicenovic *et al.*, 2000). The scenarios were both quantitative and qualitative, following the narrative 'storyline' and the corresponding models.

The SRES scenarios cover a wide range of driving forces from economic to social to demographic developments, as well as including a vast array of GHG emissions into the future. These different determinants were combined to provide a set of unique scenarios for various pathways to a future world. There were many uncertainties underlying the driving forces, not only due to the inherent uncertainty of future events, but also caused by lack of data and poor scientific understanding of many relationships

and problems. With so many unknowns and uncertainties, the IPCC chose a range of scenarios to illustrate a series of potential future developments and emissions. Since the future is mostly unpredictable, and there are many uncertainties it was not possible to select any 'best guess' or 'worst case' scenarios. The scenarios were all taken as being equally valid and all likely of occurring. The only scenarios that were not included were those thought to be 'disaster' based or 'surprise' situations. This reduced the range of scenarios, but many of such scenarios were within the 95 or 5 percentiles, the extremes of any feasible developments (Nakicenovic *et al.*, 2000).

The SRES is fundamentally a report detailing a variety of different emission scenarios. It includes anthropogenic emissions of all the relevant greenhouse gases (GHG). The scenarios included within the SRES cover a vast range of assumptions for salient driving forces, ensuring that the uncertainty of the future is adequately reflected. None of the scenarios include any future policies that explicitly address additional climate change initiatives (Nakicenovic *et al.*, 2000). Therefore there is no reference to, or assumption that, targets from the Kyoto protocol or UNFCCC are implemented. Components of each scenario cannot be mixed, but must only be used within a particular scenario. This ensures that there are no inconsistencies and the driving forces and emissions are not mixed.

5.5 SRES STRUCTURE

There is a large range of future emissions and many driving force variants, causing an infinite number of potential scenarios. The SRES cannot cover all these possibilities, but instead considers a large, finite range of emissions up to the year 2100. The approach to determine these scenarios involved selecting a set of 4 alternative scenario 'families', comprising 40 scenarios subdivided into 6 groups, see Figure 5-1 (Nakicenovic *et al.*, 2000). For each of these 'families' there is a specific 'storyline'; this was a coherent narrative that helped to facilitate the process of identifying and describing different future changes. They qualitatively discuss future developments for economies, technologies, societies and demographics. A scenario family represents the interpretations and quantifications of one storyline. The scenarios explore future changes within the world as a whole, as well as different regions of the globe, looking at interactions and differences between the developed and developing nations.

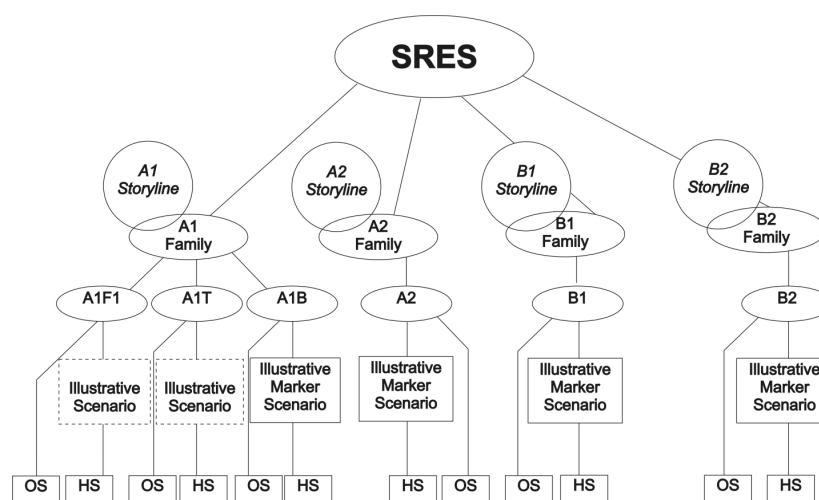


Figure 5-1: Diagram illustrating the SRES scenario structure

Source: Adapted from Nakicenovic et al. (2000)

5.5.1 Storylines

Storylines were developed for a variety of reasons. First and foremost it was a useful tool to help explain the scenarios to users less familiar with the complex nature of the models. A narrative description made the scenarios readily understandable rather than focussing on the quantitative values that make up the alternative futures. These storylines were also helpful for the writing teams, ensuring they think coherently about the involved cross-play between the driving forces and among the scenarios.

Each storyline is associated with different social, technological, economic, demographic, and environmental developments. Four storylines were selected to illustrate different futures depending on various fundamental dynamics. By selecting an even number of storylines there is no tendency to highlight one as being the most likely, or best case scenario. In the same way there is no 'business as usual' case.

The storyline titles were kept simple: A1, A2, B1, and B2, this ensured there is no ranking or implied 'best guess'. Each scenario family is based on a common specification of some of the main driving forces (Nakicenovic et al., 2000) (see Chapter 6). These scenario families describe a range of different developments from rapid technological change and swift economic growth, low and high global populations, increased commitments to environmental protection and also an array of low to high anthropogenic emissions.

5.5.2 Marker Scenarios

Within each storyline there was a 'marker' scenario; one that best embodies the storyline and has undergone the highest level of scrutiny. The markers were chosen as being illustrative of a particular storyline. However, they cannot be considered as the mean or median of a scenario family, nor can they be assumed to be more likely than

any other scenario within the family. These selected scenarios underwent the highest level of scrutiny from the writing team within the SRES. As well as under going detailed examination, the marker scenarios were rigorously tested in terms of their reproducibility. Throughout the 'open process' the markers were posted on the SRES website and any comments or suggestions were subsequently considered and implemented to the revised scenarios (Nakicenovic *et al.*, 2000).

The four SRES marker storylines (Nakicenovic *et al.*, 2000) are each characterised by different patterns in population growth, economic welfare and global emissions. They each follow a different pathway into the future. The scenarios and storylines vary significantly; they range from high to low global populations, rapid economic growth and technological development to conservative environmental strategies. Many researchers focus on the four markers in their work, for example van Vuuren & O'Neill (2006), Cranston & Hammond (2010b) and Cranston *et al.*(2010).

The marker scenarios were developed using different models shown in Table 5-1.

Storyline	Model
A1	AIM
A2	ASF
B1	IMAGE
B2	MESSAGE

Table 5-1: Storylines and associated modelling teams

5.5.3 Modelling Teams

The writing team associated with the SRES consisted of more than 50 members from 18 countries. An array of scientific disciplines, regional backgrounds and non-governmental organisations were represented. The team was led by Nebojsa Nakicenovic from the International Institute for Applied Systems Analysis (IIASA) in Austria. The teams included lead authors from the previous scenario investigations of 1990 and 1992 and the review process in 1995; this enabled a good level of continuity, familiarity and expertise with the scenarios to efficiently complete their development and evaluation.

The six modelling teams were based in Europe, Japan and North America, using different modelling techniques (see Table 5-2). They were chosen since they represent a variety of approaches to modelling emissions scenarios and different assessment techniques, including top-down and bottom-up models. They were also representative of three different continents, and as such were appropriate to help develop the many varied scenarios required within the SRES.

	Model	Modelling Team
<i>AIM</i>	Asian Pacific Integrated Model	National Institute of Environmental Studies, Japan
<i>ASF</i>	Atmospheric Stabilization Framework Model	ICF Consulting, USA
<i>IMAGE</i>	Integrated Model to Assess the Greenhouse Effect	National Institute for Public Health and Environmental Hygiene, Netherlands
<i>MARIA</i>	Multiregional Approach for Resource and Industry Allocation	Science University of Tokyo, Japan
<i>MESSAGE</i>	Model for Energy Supply Strategy Alternatives and their General Environmental Impact	IIASA, Austria
<i>MiniCAM</i>	Mini Climate Assessment Model	Pacific Northwest National Laboratory, USA

Table 5-2: Modelling teams for SRES

5.5.4 Four SRES World Regions

Throughout the development of the scenarios different regions were considered. A total of four regions were selected, or 'macro-regions', that were by and large consistent with the United Nations Framework Convention on Climate Change (UNFCCC, 1992). These regions were labelled as the OECD90, REF, ASIA and ALM. The OECD90 and REF regions can be combined to represent the developed countries, as described in Annex I and the ASIA and ALM regions correspond to the developing countries in non-Annex I (UNFCCC, 1992). The regions can be broken down further as such (Nakicenovic *et al.*, 2000):

- **OECD90:** this region represents all those countries within the Organisation for Economic Cooperation Development (OECD) from 1990. This was the base year for the scenarios.
- **REF:** this region groups the countries undergoing economic reform and thus contains Eastern Europe and the Newly Independent States of the former Soviet Union.
- **ASIA:** this region represents all developing countries in Asia (excluding the Middle East).
- **ALM:** this region corresponds to the rest of the world, including all developing countries in Africa, Latin America and the Middle East.

The details of these regions and which countries are included within each group can be found in Appendix B.

5.6 KEY DRIVERS FOR SCENARIOS

The storylines described in the SRES represent different environmental, economic and social dimensions. They can be fundamentally classed into two dimensions, globalisation or sustainability. These classes describe the extent of social and cultural interactions and economic convergence, represented by globalisation, and the careful balance between economic growth and achieving environmental objectives, represented by sustainability. The four scenario families could be separated according to these issues (Figure 5-2). The A1 and B1 storylines highlight economic convergence and social and cultural interactions on a global scale, albeit to different degrees of success, whilst the A2 and B2 families follow more regionally based pathways to development. In terms of sustainability, the split is different: the A1 and A2 storylines follow an economic drive pattern, where improved levels of affluence is of a higher priority than environmental protectionism; the B1 and B2 families contrast by orientating the main concern towards environmental issues rather than aspiring to high levels of economic development and growth.

Each of the storylines details the basic driving forces for different sets of scenarios (see Chapter 6). Every scenario is associated with a particular storyline, and as such can be grouped into a scenario family. The storylines branch out into the different paths that are possible within each scenario family; this is indicated by the four separate groups highlighted for the A1 case (see Figure 5-2).

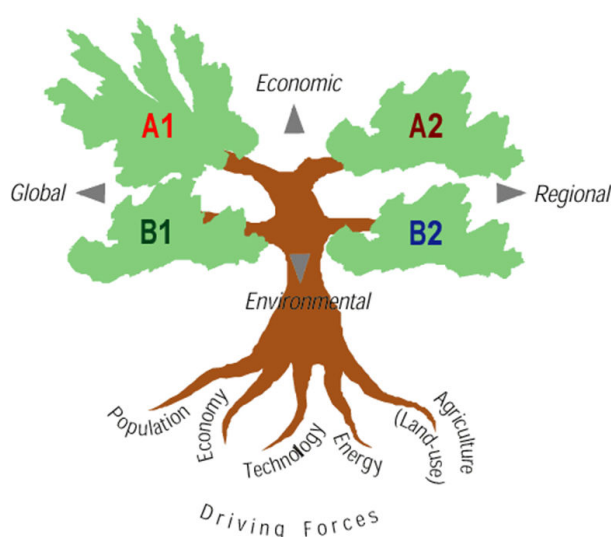


Figure 5-2: Schematic illustration of SRES scenarios

Source: Nakicenovic et al. (2000)

5.7 BREAKDOWN OF THE FOUR STORYLINES

5.7.1 A1 Family

The A1 storyline presumes convergent economic development between regions, an ultimately decreasing world population (by 2100), and abundant energy and mineral resources (due to rapid technological progress). This scenario is driven by the internationalisation of people, technologies and ideas, and a commitment to market-based solutions. The A1 scenario family develops into three groups, each describing the alternative directions of technological change in energy systems.

The A1 storyline represents a world with rapid economic development and growth, together with the implementation of advanced efficient technologies. There is regional convergence in terms of per capita income, such that the divisions between rich and poor nation states slowly disappear. This economic transition and convergence is attributed to the advances in transportation and communications as well as changes in policies for immigration and education and a commitment to the national and international institutional development that encourages a cross over of productivity and growth, mobilising people and ideas.

Population growth was estimated to peak in mid-21st Century and then began to decline; total global population reaches 9 billion by 2050, and finally decreases to 7 billion by the turn of the century. The changes in demographics are closely related to economic developments, since affluence is correlated with small families and long life (Nakicenovic *et al.*, 2000). Populations tend to age, but the retired communities are able to support themselves having accumulated savings through private pension schemes.

Economic growth approximately follows the average global rates from 1850, reaching US\$550 trillion by 2100 (Nakicenovic *et al.*, 2000). This high level of growth improves the social conditions and health care for many people, but there still exists social exclusions and economic pressures. There was assumed to be an internationalisation of people as regions began to converge with increased social interactions and less significant differences in economic income. Therefore there are far less regional differences in per capita income. Due to the increase in affluence, there is an increase in meat eaters and consumption of dairy products, as well as an increase in car ownership and subsequent dense transportation systems both nationally and internationally.

The A1 storyline follows a rapid introduction of new and very efficient technologies that causes energy intensity levels to reduce. This ensures that resources are abundant since output levels are higher for a given amount of energy. Environmentalism is not strong in this storyline; rather than making efforts to conserve natural capital, there is an emphasis on managing Nature's services. There is a split within the A1 family to different energy based solutions. Some scenarios follow pathways that coincide with

countries having plentiful coal supplies resulting in carbon intensive industries. Other scenarios use oil and gas supplies, whilst the final group tend towards renewable energy sources. The A1B marker scenario constitutes a balanced mix of technologies and different resources such that no single energy source is seen to be dominating.

5.7.2 A2 Family

The A2 scenario assumes more self-reliance in terms of resources, and there is less economic, social and cultural interaction between regions than is associated with A1; the world is far more heterogeneous. Economic growth in the A2 scenario is more uneven with little inter-regional convergence. There is a strong preservation of local identities and high population growth due to a very slow convergence of fertility patterns across regions.

The A2 scenario family represents high self-reliance within regions. In comparison to the A1 storyline trade flows are lower, technological advancement is slower and there is far less importance placed on integrating economic, social and cultural characteristics between regions. The interactions between regions are few, with little international cooperation, contrasting to the A1 and B1 situations. This gives rise to very slow sharing of ideas and technologies as people and indeed capital are far less mobile. There is therefore no convergence between the industrialised and developing worlds in terms of the income gap, as is represented characteristically in the A1 and B1 storylines. Global income is relatively low, reaching US\$250 trillion in 2100 (Nakicenovic *et al.*, 2000).

There is a very strong emphasis on family and communities and this has an effect of causing fertility rates to decrease at a slow rate, resulting in very high population predictions. Indeed the A2 scenarios have the highest population by 2100 at 15 billion (Nakicenovic *et al.*, 2000). Population growth is uninterrupted throughout the century for all the SRES regions.

Technology advancement is disparate among the regions. Some regions have good technological development, whilst others are very slow due to the lack of homogeneity throughout the world (Nakicenovic *et al.*, 2000). Instead regions develop according to local resources, cultures and education. Those regions with excellent resources tend to develop technologies and economies that are resource intensive; other regions with less abundant energy resources compensate by improving efficiency for resource use and using substitutes. For all regions food supplies are vital due to the booming populations. Therefore a large focus is placed on developing agricultural productivity and innovation.

5.7.3 B1 Family

Environmental and social consciousness is a high priority for the B1 scenario family, aimed at moving towards a globally coherent, sustainable future. There is a large

amount of attention paid by governments, businesses and the media to environmental issues, causing many technological changes and advances. The impact of overusing natural capital is better understood such that effects of, for example, deforestation and over-fishing, are understood in terms of the threat they pose to humanity's existence on the Earth.

The development of global economies is balanced within this storyline. In a similar manner to the A1 storyline, the B1 storyline represents a fast developing and convergent world, however the emphases are different. Any financial gains or technological developments are reinvested to improve environmental protection, resource use efficiency and social welfare, as opposed to the A1 scenario families where investments are made to further productivity and affluence. There is a high level of economic activity, resulting in a total global GDP of US\$350 trillion by 2100, but this is spent on quality rather than quantity, investing in services rather than material goods (Nakicenovic *et al.*, 2000).

The B1 storyline shows a reduction in material intensity and an introduction of clean and efficient technologies; the priority towards resource efficiency is greatly increased. There is an emphasis on a service and information economy with advanced technologies in order to be sparing in the consumption of resources. Not only is technology advanced, but organisational structures are altered to encourage recycling, reuse and reduction of materials. Incentives also promote the diffusion of clean technologies and labour productivity is improved. There is a move to cleaner energy resources and much development of alternative fuels and post fossil fuel technologies. Cities are designed to be compact and efficient, with integrated public transport systems that are non-motorised. Wildernesses are preserved, which causes an increase in food prices; this contributes to the decline of meat eaters, also encouraged by public understanding of sustainable development.

The B1 scenario family follows the same 'peaking' and low population growth pattern as A1, with low mortality and fertility rates; however, these trends are the result of different drivers, motivated by social and environmental protectionism. The demographic transition towards lower fertility rates are also caused by better education and improvements in the social standing and development of women.

5.7.4 B2 Family

The B2 scenarios have a similar storyline to that of A2, but with more focus upon climate change mitigation, which is addressed through local community-based solutions. There is a moderate population growth and intermediate level of economic development. In a similar fashion to B1, the B2 scenarios have a heightened concern for sustainable development, but at a more regional level looking towards local solutions. Community based solutions are implemented in reaction to an increased feeling of environmental protectionism, human welfare and equality.

Population growth follows the UN and IIASA median projections, growing continuously, but at a lower rate than the A2 situation. The global economy expands at an intermediate rate to reach US\$250 trillion by 2100 (Nakicenovic *et al.*, 2000). International equity is met very slowly with small changes in the income gap between regions, however local inequity is reduced considerably by the development of community support networks.

Development is based very much on local communities, as such there are few global priorities that link all the regions together, the one exception being a desire to move along the sustainable development pathway. Despite this, there is little interaction between governments to establish worldwide commitments and strategies towards solving environmental problems.

Technological change is uneven throughout the world. Some regions undergoing rapid economic development but with limited resources have the capabilities to invest in developing technologies to solve their problems locally (Nakicenovic *et al.*, 2000). In the same way energy systems vary from region to region.

5.8 LIMITATIONS OF SRES

The SRES scenarios are well reported and often adopted by researchers. However, they are not without limitations or problems. They have been criticised for being out-dated with many more recent projections suggesting far lower populations and different economic growth trends. The macro scale of the scenarios has also been criticised as the SRES scenarios only represent global regions, and do not consider national or sub-national scales. A finer spatial resolution was investigated by Arnell *et al.* (2004). However, there is far more uncertainty associated with such downscaled models, due to the level of detail necessary not only for one year but future years. Girod *et al.* (2009) maintain that the IPCC scenarios have grown in credibility and the SRES is far more sophisticated, although needs clearer traceable storyline construction. The IPCC plan to release their latest updates in answer to the critiques in 2014 – the Fifth Assessment Report.

The scenarios developed for the IPCC SRES report might be viewed as rather dated, because they utilise early datasets (Nakicenovic *et al.*, 2006). New forecasts are necessary to ensure that the most recent data and their forward projection are employed, old thinking is challenged, and better estimates of uncertainties utilised. The population trajectories were the main area where recent forecasts have been made that differ significantly from those used in connection with the SRES projections. There have consequently been many comparisons of new population trajectories with those associated with the original SRES scenarios; see, for example Fisher *et al.* (2006), Hulme (2009), Lutz *et al.* (2004), Lutz & Sanderson (2001), and Nakicenovic (2000).

It has been recognised by a number of researchers that the SRES scenarios assume too rapid economic growth, and that population trends are unlikely to be so high. Indeed it has been noted that in the long-term between 2 and 4 billion fewer people are expected to inhabit the planet by 2100 across the range of predictions (Nakicenovic *et al.*, 2006). Interestingly, when studies have incorporated the new, more conservative, population projections, the changes in other drivers (such as economic growth) result in little change to overall GHG emissions (IPCC, 2007b). The IPCC have themselves stated that, although population scenarios from major demographic institutions are lower than they were at the time of the SRES, they have not been fully implemented in the GHG emission projections found in the recent literature (IPCC, 2007a). However, van Vuuren and O'Neill (2006) consider that there is no real reason to initiate a complete update of the SRES scenarios, since they regard the inconsistencies in global trends as being relatively small. But they recognised that scenarios do have a limited 'shelf life', and that the data upon which they are based clearly becomes outdated over time. The appropriateness of the population and GNP projections used by the IPCC was therefore re-examined here.

5.8.1 Inconsistencies in Population Projections

The population data used in the SRES study has caused some controversy among researchers. Nakicenovic *et al.* (2006) assessed various scenarios and projections made after 2001, and compared them with the SRES and Third Assessment Report (TAR) scenarios. They found that population projections varied significantly. Indeed population was highlighted as being the major driver that needed to be revised, because major reductions in total global populations were likely by 2100 compared to earlier estimates. In order to determine whether the SRES scenarios were appropriate for use in this thesis, the population trajectories for each marker storyline were compared with the latest data available from the International Institute for Advanced Systems Analysis (IIASA) (Lutz *et al.*, 2001; Lutz *et al.*, 2007) and the United Nations (UN) (Department of Economic and Social Affairs, 2004). The most recent IIASA data (for 2007) is significantly different to that available in 2001. There are similar discrepancies in comparison to the UN data (for 2004), although with a much smaller range and far lower maximum population estimated for 2100. However, the medium value for projected population size is consistent with the other data sets (see Figure 5-3).

It became evident, from comparing the latest population projections with those obtained using the original SRES marker scenarios that the A2 scenario was out of the range suggested by the latest predictions from the IIASA and UN (see Figure 5-3). Indeed, even the updated 'A2r' case provided by Riahi *et al.* (2007) was above the range of the 2007 IIASA estimates. Riahi *et al.* (2007) considered the A2r and B1 scenarios to bracket the upper and lower quadrants of emissions, taking the B2 storyline as a more intermediary scenario. The B1 and B2 scenarios for population, on the other hand,

display good agreement with recent demographic projections from both the IIASA and the UN.

Despite the fact that the A2 scenario falls above the range of more recent datasets projections, van Vuuren & O'Neill (2006) suggest that it does not imply that such scenarios are not likely. This is because of the level of uncertainty and error associated with projections. Since no individual scenario in the SRES has a probabilistic value attached to it, it is possible to accept those scenarios that are slightly outside the bounds of the more up to date projections.

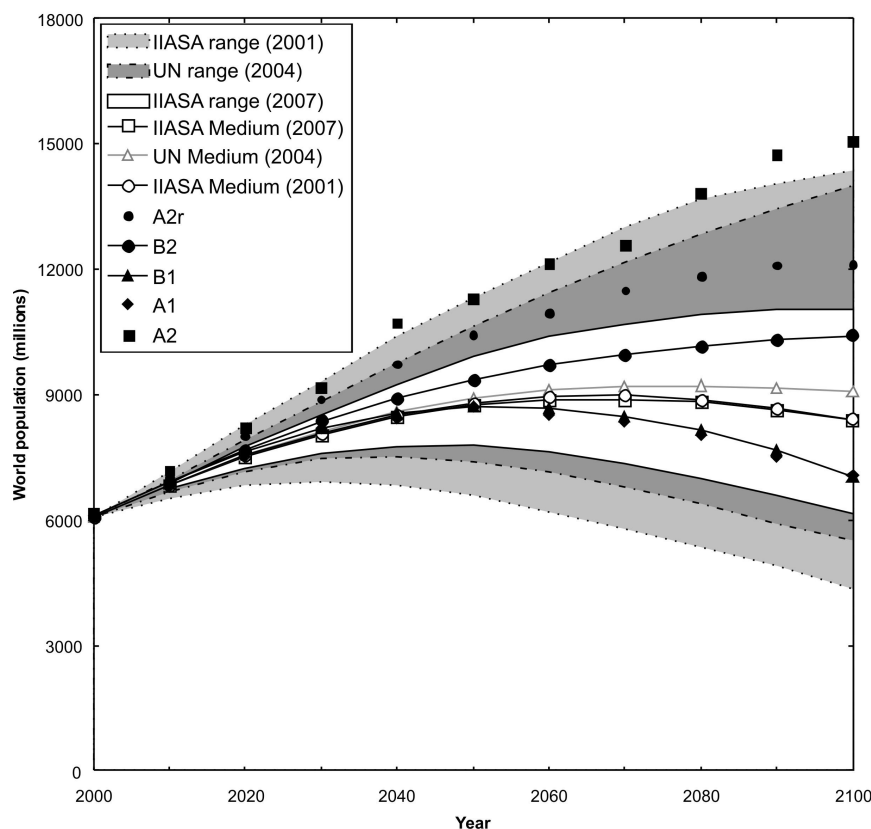


Figure 5-3: World Population Projections

5.8.2 Variations in Long-term Economic Growth Forecasts

Nakicenovic *et al.* (2006) determined that the economic development estimates haven't varied significantly between the old and new literature; the medians and percentile distributions were essentially the same. Unlike the population trajectories, there are no official organisations that make global economic growth projection into the long-term future. Therefore the only information available is sourced from researchers in the field of climate change studies, who generate scenarios and corresponding projections as part of their work. In order to determine the applicability of the SRES economic growth projections, the marker scenarios were compared with two other academic sources (Riahi *et al.*, 2007; Weyant & de la Chesnaye, 2006); see Figure 5-4 below. Both Riahi *et al.* (2007) and Weyant & de la Chesnaye (2006) (from the Energy Modelling Forum,

EMF) consider economic growth to be the most important determinant of future emissions. Figure 5-4 suggests that the SRES economic growth projections are still within the bounds of these more recent estimates; A1 is the only projection that is significantly out of line. van Vuuren and O'Neill (2006) suggested that this may be because the A1 marker scenario represents a very high growth rate for the Africa and Latin America (ALM) region. A1 and B1 are both above the mean values suggested by Weyant & de la Chesnaye, whereas A2 and B2 fall below their trends. A2 has a slightly unusual pattern, as it exhibits a low economic growth, but rapid population growth. However, up to about 2070 it seems representative of low economic growth forecasts. The SRES projections were found to be consistent with recent economic growth scenarios (see Figure 5-4); fitting within the appropriate range forecasts.

A debate has surrounded the way in which the income projections of the IPCC were expressed in terms of *Market Exchange Rates* (MEX), rather than *Purchasing Power Parity* (PPP) (Hammond, 2006a). Its working group considered (IPCC, 2003) that over long time periods the values for economic growth in terms of MEX and PPP tend to converge for less developed regions. Studies have shown that the choice of exchange rate for GDP does not greatly affect the projected GHG emissions if used consistently (IPCC, 2007a; IPCC, 2007b). Indeed, despite being the most highly debated aspect of the SRES scenarios, the economic growth trends do not vary significantly (IPCC, 2007a).

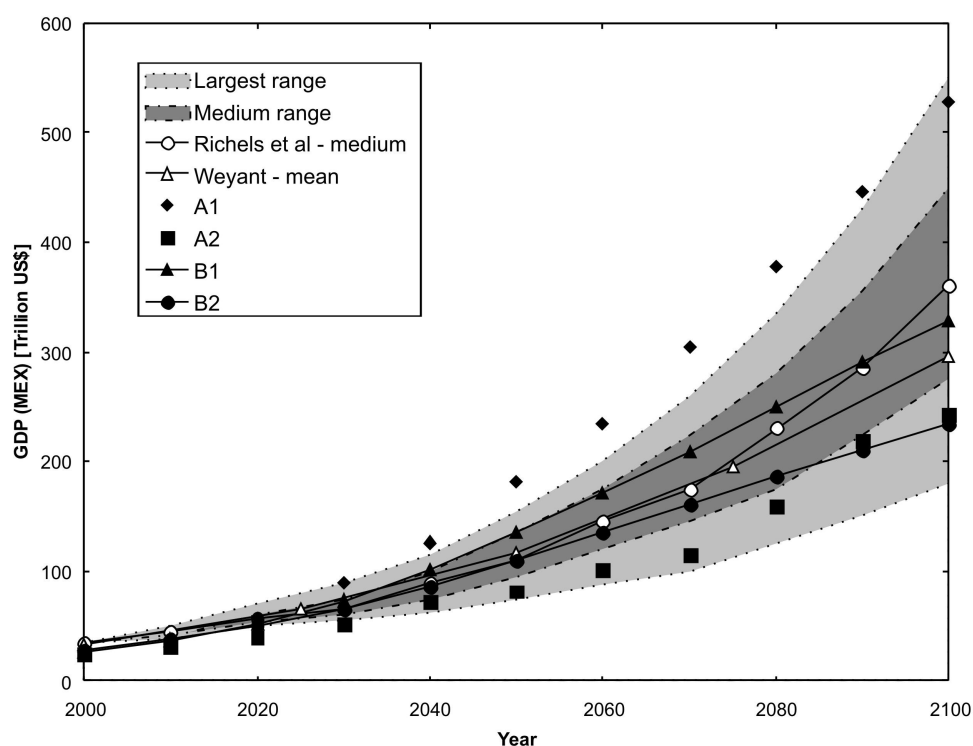


Figure 5-4: World GDP Projections – SRES Markers and Updated Scenarios

It remains that, although the new projections offer differences particularly for population trajectories, the SRES scenarios are driven by other factors and thus the change in GDP and population values actually contribute to a small change in the overall emission levels (Bernstein *et al.*, 2007). The scenarios are intrinsically linked to the many differing factors and assumptions that are outlined in the storylines, and individual, updated projections of say, population growth, cannot be taken as stand alone data, but needs to be integrated within the scenario models in order to be useful in making trajectories of climate change into the future. van Vuuren & O'Neill (2006) suggest that there is no need for an updated IPCC led study due to the relatively small inconsistencies for global scenarios. They state that the SRES scenarios are still credible, but that there is a lack of representation in the lowest range of population projections. If the SRES were to be updated, a focus upon low population growth would be necessary and advisable.

5.8.3 Carbon Dioxide Inconsistencies

Originally when Nakicenovic *et al.* (1998) made their first scenario assessment, the carbon dioxide emissions range was large. More recent estimations for carbon dioxide scenarios maintain the large and varied range; this contrasts with the significant reductions in population data in recent literature.

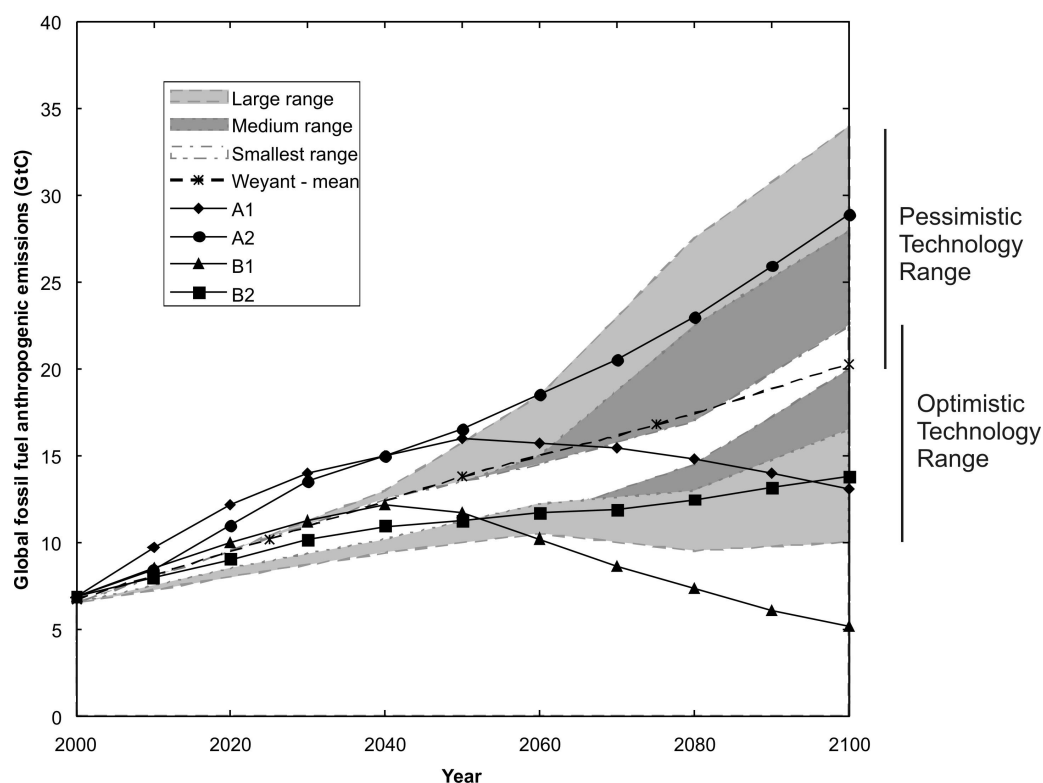


Figure 5-5: Comparison of global fossil fuel emissions for marker scenarios and updated CO₂ emission scenarios

Unfortunately there are no long term projections for carbon dioxide emissions from any official institutions. However, van Vuuren & O'Neill (2006) compared the SRES marker scenarios with the currently available literature and found that the SRES scenarios follow a similar range. Nakicenovic *et al.* (2006) also demonstrated that the carbon dioxide emissions have not changed dramatically since the SRES was published. Figure 5-5 shows a comparison of the four marker scenarios with recent literature updates from Richels (2004) (shown as a range) and Weyant & de la Chesnaye (2006). The B1 scenario is significantly lower than the updated range towards the end of the twenty-first century, but this should be expected because of the nature of the scenario (B1 has a strong focus upon improved energy efficiency and developing technologies). The updated projections are more focussed around the median values up to the middle of the century, whilst SRES scenarios demonstrate more pessimistic carbon emissions up to 2050, with the final range in 2100 lower than expected by the more recent studies. Nakicenovic *et al.* (2006) collected 213 scenarios published since 2001, following the SRES report, and compared these to the 482 pre 2001 scenarios (Figure 5-6). This not only highlights the vast selection of scenarios available, but also indicates the latest trend towards lower projected carbon emissions, with much of the new literature data being clustered together in the lower percentiles. The reason for this is that some scenarios assume that mitigation policies and intervention methods are implemented to prevent carbon dioxide atmospheric concentrations increasing exponentially. By comparing Figure 5-5 and Figure 5-6 it can be seen that the SRES scenarios remain within the range of current trajectories. Indeed, van Vuuren & O'Neill (2006) consider the SRES assumptions for carbon dioxide emissions to be credible since they are consistent not only with historical data but also with a variety of recent projections. Nakicenovic *et al.* (2006) recommend that the range of emissions have not changed significantly since the publication of the SRES, and it is therefore acceptable to utilise the SRES scenarios.

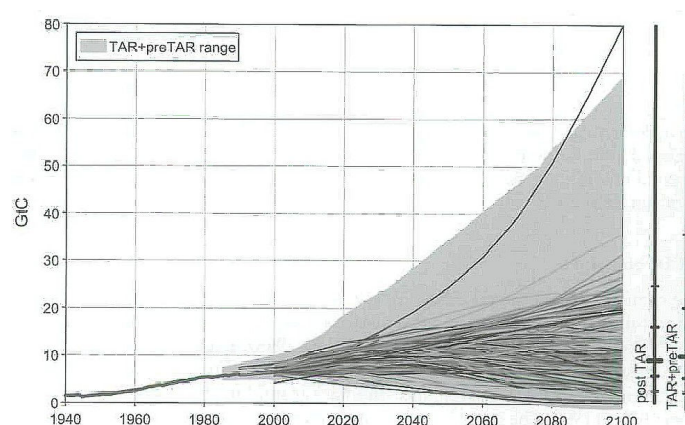


Figure 5-6: Global carbon emissions, historical developments and scenarios

Shaded area represents 482 scenarios published before 2001, curves represent additional 213 scenarios published post 2001. Vertical lines to the right hand side indicate the range of scenarios pre 2001 (TAR + pre TAR) and post 2001 (post TAR).

Source: Nakicenovic *et al.* (2006)

5.8.4 Global Financial Crisis

Many scenarios were projected well before the recent economic crisis (Nakicenovic *et al.*, 2000) and thus do not take into account the effects of recession in many countries and the subsequent impacts upon industry and energy use. It is necessary to consider whether the economic crash will induce a permanent loss, levelling off or growth in output and how this may influence scenarios.

The financial crisis of recent years (IMF, 2009) has had a large effect upon the energy sector worldwide. As well as impacting global economies the IEA estimated that CO₂ emissions could fall in 2009 by as much as 3%, this could cause emissions in 2020 to be 5% lower than has previously been anticipated (IEA, 2009a). This offers the world an unprecedented opportunity to make significant changes to stabilise GHG emissions and global temperatures.

It was accepted that it is too early to make a definitive judgement regarding the effects of the economic problems, and that even with better understanding of the financial crisis and its impacts, long term economic growth projections are inherently speculative with large uncertainties (Duval & de la Maisonnette, 2010). It was assumed that the financial crash would not have a major impact upon the regional and worldwide scenarios since total global economic values may not be affected so intensely. The timescale of the SRES scenarios is so long that this 2-3 year spate of economic crisis won't have a significant influence on the projections of economies at the end of the century.

It is too soon to be able to make long-term estimates about global economies, markets and energy use based upon the recent financial downturn, and without any detailed analysis and data available it was necessary to utilise the IPCC SRES scenarios. It would be most illustrative and informative to revisit these studies with appropriate information regarding the worldwide economies and their recovery. In conclusion, it is currently not possible to include estimates resulting from the global financial crisis.

5.9 SUMMARY

Scenarios are important to assess future alternatives and are necessary to encourage the ongoing global assessment of climate change. They are in no way predictions or forecasts, but simply represent a variety of contrasting pathways into the future.

There is a wide selection of scenarios available; however the IPCC SRES was selected for use in this thesis. The IPCC is an internationally regarded body, and many researchers, businesses and governments use their scenarios and results. Therefore, the IPCC scenarios were accepted as appropriate for the work undertaken in this thesis, and their markers – A1B, A2, B1 and B2 – were utilised to model different pathways of transition to a future world (see Chapters 10 and 11). These storylines represent very different worlds. The A1

represents convergent economic development between regions, an ultimately decreasing world population by 2100. A1 is determined by globalisation. The A2 scenario describes a more self-reliant world particularly with respect to resources, and there is less interaction between regions. There is uneven economic growth in the A2 scenario. The B1 scenario assumes a high level of environmental and social consciousness, with a global strategy focused on sustainable development. A balanced economic development is presumed, with any financial gains being invested into areas such as environmental protection and improving resource efficiency. Finally, the B2 scenario follows a storyline close to that of A2, but with a greater focus upon climate change mitigation.

The IPCC scenarios differ from other scenario projections since they explore a wide variety of possible futures, whilst many alternative scenarios focus on only a few 'most likely' outcomes. The SRES scenarios have been shown above to be within the range of plausible outcomes suggested by other scientists and are not biased towards, for example, a particularly energy efficient or monetary driven world. They also adopt a long timescale, up to 100 years.

CHAPTER 6

DRIVING FORCES FOR THE FOOTPRINT AND SCENARIOS

6.1 INTRODUCTION

Footprints vary between countries at different stages of economic development and with contrasting geographic characteristics. The size of national footprints is dependent upon many parameters; not only on the geographic location of the country, but also on its population size, technological advancement and economic well-being. For example, nations with populations having the luxury of expendable incomes inevitably have far higher consumption rates than those poorer states with little wealth. The contrast in consumption levels between such nation states will affect the differing sizes of their ecological footprint, particularly the energy land segment which tends to dominate the footprint. The bioproductive land section of the footprint, on the other hand, is more likely to be affected by factors such as climate and topography. As such, the ecological footprint can be considered to be a function of a variety of parameters, ranging from economic welfare to geographic characteristics to climatic factors.

The work within this chapter highlights the important drivers behind the footprint and also those that are fundamental to scenario formulation and considers the inter-relations between these factors.

The IPCC scenarios (Nakicenovic *et al.*, 2000) are adopted throughout this thesis (Chapters 5, 10 and 11), and the driving forces behind these predictions must be considered in order to fully understand the implications and subtleties of each scenario result.

6.2 AN INTRODUCTION TO THE 'IPAT' EQUATION

The factors that were postulated to affect the footprint have also been considered within scenario calculations (Nakicenovic *et al.*, 2000). The major driving forces for emission scenarios consist of population, economics, demographics, technology, and resources. The IPAT equation (equation 6-1) is frequently used to organise the drivers of emissions.

$$\text{Impact} = \text{Population} \times \text{Affluence} \times \text{Technology} \quad 6-1$$

This equation can be used to state that environmental impact, such as carbon emissions, are the product of population levels, affluence (per capita income) and technology (emissions per unit of income). The IPAT equation is often manipulated to explicitly

identify carbon emissions (equation 6-2), see for example Gurer & Ban (1997); the expression is known as the Kaya identity (Kaya, 1990).

$$\text{CO}_2 \text{ emissions} = \text{Population} \times \frac{\text{GDP}}{\text{Population}} \times \frac{\text{Energy}}{\text{GDP}} \times \frac{\text{CO}_2}{\text{Energy}} \quad 6-2$$

This identity can be further broken down into other components, such as fossil and non-fossil based fuels for the energy component. Since the expression is a multiplicative identity, the component growth rates are additive (Gurer & Ban, 1997; Nakicenovic *et al.*, 2000) (see Chapter 11).

It may appear that carbon emissions grow linearly with population; however, the interactions between each component are more complex, varying between demographics and economic growth. Many of the factors are interlinked; for instance, demographic changes are related to differing social and economic developments. Fertility and mortality trends are dependent upon income, education and health education, and these in turn affect the size and age of populations (Nakicenovic *et al.*, 2000). Advances in technology cause improvements in economies in terms of productivity and growth. This illustrates that affluence and technology cannot be treated as totally separate within the IPAT and Kaya identities.

Income was also assumed to be heavily linked with pollution abatement. A rise in income, combined with attitudes for environmental protectionism, should cause an initial rise in pollutants, but gradually allow for a reduction in emissions, following the well known shape of the Kuznets Curve (Huang *et al.*, 2008) (see also Figure 11-5). Technology, social and economic changes are often regarded as enabling growing populations to live within their restricted resources. Such innovations occurred, for example, during the Industrial Revolution, when the use of primary energy was developed through changes not only in technology but developments in the economy as well, which subsequently impacted upon societal transitions.

The impacts of different determinants within the IPAT and Kaya identity were considered to be directly translatable as having an effect upon the environmental and carbon footprints around the globe. However, since the footprint is a complex tool, with many different inputs, complex interactions and land based units, a variety of additional driving forces were considered important (see Chapter 8).

6.3 POPULATION PROJECTIONS

Population growth is often mooted as being one of the main contributors to the expanding carbon emissions, draining the Earth's natural capital and having a negative effect upon environmental quality. Despite the fact that approximately 80% of the world's population resides in the developing world where their consumptive behaviour

is far more frugal than the industrialised regions, this growing population was considered to have an affect upon ecological footprints.

The world's population is continually growing; even at the current level humanity is overshooting the Earth's capacity to provide for everyone (WWF International, 2008). Every person on the planet has the need for food, clothing and shelter, as well as the demand for energy for heating, transportation and industry. An increased population will augment these demand levels and, as resources become more scarce, it is difficult to fulfil the needs of all the people of the World. Population increases can also result in deforestation in order to accommodate larger populations in terms of habitat, fuel and food; it will thus have an effect upon other changes in land use. Of course population growth can be argued as having a positive impact; there are more likely to be vigorous developments of technology and science, and humanity will have a better opportunity to establish technological solutions to environmental problems (Shi, 2003). However, Shi (2003) was able to show that the Malthusian view that population growth has an adverse effect on emissions is supported more strongly over the last two decades, particularly for those developing regions of the world. The debate that technological development can respond to environmental pressures is only supported within the highest income nation states (Shi, 2003).

6.3.1 Drivers Influencing Population Growth

There are four main bodies that generate population projections (Nakicenovic *et al.*, 2000): United States Census Bureau, World Bank, United Nations and IIASA. Each of these institutions makes estimates for future populations, generally indicating high, medium and low variants. Many of these trajectories are comparable, due to the use of similar methodologies among the bodies. It is assumed that the key drivers behind changes in population are fertility and mortality rates, aging, urbanisation and the spread of HIV and AIDS (Nakicenovic *et al.*, 2000). Fertility is the most important factor affecting population size. Many scenarios assume a decrease in world averaged total fertility rate (the average number of births per woman). A small change in fertility rates can cause a massive variation in future populations. Fertility rates are expected to continue to decrease in developed regions, such as Europe (Pearce, 2010). However, demographers believe that this may be due to women deciding to delay childbearing until their later years, and as such the total fertility rate may begin to rise in the long-term (Nakicenovic *et al.*, 2000).

Population was expected to have relationships with other factors, such as economic welfare and emissions. Indeed, Gaffin & O'Neill (1998) argue that CO₂ emissions are strongly affected by population growth. In terms of economic growth, the common assumption is that wealthier countries have a relatively low fertility rate, whilst those poorer countries tend to have higher fertility rates on average. As families make the transition into wealth, goods and services become more readily available, and consumption tends to increase. As such, there is a shift from high to low fertility as

families make the choice to consume more, as opposed to having more children. This often tallies with urbanisation.

6.3.2 Population Scenarios

Population growth has long since been estimated and is commonly cited to be indicative of future changes in the World's development. They are similar to emissions scenarios in that they vary with changes in economic wealth and social consciousness and they often cover very long time scales. Population trajectories are one of the relatively accurate projections within the scenario discipline for near-to-medium term estimates (Nakicenovic *et al.*, 2000). Despite this, there are always some unforeseen circumstances or events that cause the projections to prove inaccurate, and indeed there is a fair amount of uncertainty associated with these scenarios. Historically examples include the baby boom following the end of the Second World War, and more recently humanity is experiencing a decrease in fertility among women in the developing countries (Nakicenovic *et al.*, 2000).

The SRES scenarios utilise population projections from the UN and IIASA (Lutz, 1996; UN, 1998). These datasets are publically available and have more than one central demographic projection which allows for an assessment of uncertainty. The medium UN projection is adopted since it has been recognised internationally and follows the replacement-level fertility that was required for long term scenarios. The IIASA data was utilised for the 'high' and 'low' variants, since they include relationships between fertility and mortality rates and represent an appropriate uncertainty range (Nakicenovic *et al.*, 2000). The three population projections were adopted within the 'harmonised' scenarios, whilst other scenarios explored a variety of population trajectories consistent with the storylines.

Population trends were considered in the SRES over a timeframe of a century and looked at both global changes and regional differences. Historical growth rates were analysed, which indicated a marked difference in population distribution and growth between major geographic regions. Indeed, the developing world saw an increase in population from 1.71 to 4.59 billion between 1950 and 1996 (UN, 1998) with a maximum growth rate of 2.5%, levelling out to 1.7% in 1996. This was in contrast to the growth rates in more developed regions of 1.2% in 1950 reducing to 0.4% (UN, 1998), representing an increase in population of just under 400 million.

It has been discussed (in section 6.3.1) that there is a link between population, fertility rates and economic development, such that there may be an inverse correlation. Despite this qualitative assumption, no population trend was directly associated with an economic trend since income could not be assumed to predict changes in demographics alone (Nakicenovic *et al.*, 2000).

Three different population projections were applied to the SRES marker scenarios (A1 and B1 follow the same population trend). A range of 7 to 15 billion people were estimated to inhabit the world in the year 2100. The A1 and B1 scenario families both assume the same population trajectory, this being the lowest projection based upon Lutz (1996). This follows low fertility and low mortality trends as well as a central migration rate, assuming that fertility rates would fall below replacement levels. As can be seen in Figure 6-1 the population is expected to increase up to the middle of the 21st century, peaking at 8.7 billion and then decreasing down to 7.1 billion by the end of the century. The B2 scenario family adopts the median population projection of the UN (1998), such that the current and historical trends are continued but within time will flatten out to a constant level. This combines the fast rates of declining fertility and mortality that has currently been experienced. The World's population steadily increases to 9.4 billion by 2050, but then begins to slow in pace, increasing by only 1 billion up to 2100. This population projection implements the very slow population growth within the developed world, and assumes that there will be a stabilisation among the population growth in Asia by the mid-century, and populations elsewhere in the world will have stabilised towards the end of the century (Nakicenovic *et al.*, 2000). The A2 scenario family was characterised by the highest population growth, based upon very high expansion, reaching 15 billion by 2100 as reported by Lutz (1996). This assumes small declines in fertility and an evening out at above replacement levels.

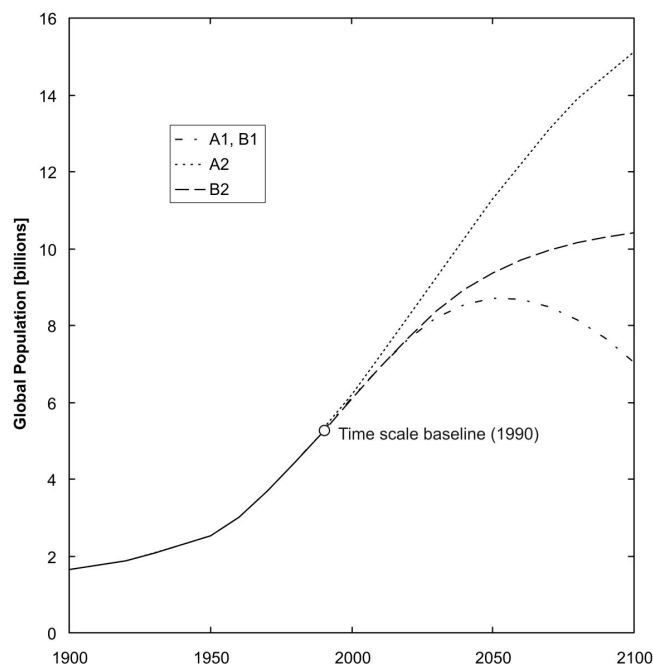


Figure 6-1: Global population projections and historical data for SRES scenarios

6.4 ECONOMIC EXPANSION

Ecological footprints are fundamentally driven by the utilisation and expenditure of natural capital. They measure how much of Nature's resources an individual or

population use in a given year. This is not dependent upon basic needs or requirements but is evaluated purely by the lifestyle and habits of a given group. Those living in impoverished conditions with little or no available money will therefore consume far less than those who can afford to live above the poverty line, purchase luxury items and belongings surplus to requirement. Economic welfare was thus considered to have an important influence upon the size of ecological footprints. Interestingly, the argument that societies become “greener” and thus more sustainable as they generate wealth has been disputed by Vogelsang (2002), who uses the footprint to highlight the reality of biophysical constraints (Vogelsang, 2002).

Countries throughout the world are at varying stages of economic development. Some have entered the stage of mass-consumerism, such as the United States of America, some are undergoing transition, catching up to the ‘productivity frontiers’ of the developed world, such as China, whilst others are at very low level productivity levels, with strong links to agriculture and slow economic change. The tendency is for those countries undergoing economic transition to have the highest growth rates as they strive to overcome the technology and productivity frontiers that stand before them.

Globally, per capita GDP has increased 1.2% faster than population growth (Nakicenovic *et al.*, 2000). In the last 110 years, total GDP for the world increased by twenty times, representing a five-fold increase per capita (Nakicenovic *et al.*, 2000). Economic growth has historically tended to be centralised around Australasia, the Americas and Europe. However, recently there have been high levels of per capita economic growth in Asia, and a gradual slowing down of growth within the OECD countries.

6.4.1 Driving Forces behind Economic Development

There are a variety of driving forces behind economic development, including population, demographics and societal change. Economic growth can be realised through the development of inputs such as labour and capital, or by enhancing productivity. Population growth is often regarded as important in developing economies as it offers a larger work force, however, more detailed analysis shows that many social and institutional factors increase economic development; for example, encouraging female participation in the work force and education provide opportunities for economic stimulation and encouraging social improvement in the long term (Nakicenovic *et al.*, 2000).

Historically carbon emissions have increased at a rate of 1.7% per year on average (Nakicenovic *et al.*, 2000) since 1900; were this trend to continue, global emissions would double within 40 years and increase by 6 times by the end of the century.

An aging populace has been identified as one of the potential changes in demographics (Nakicenovic *et al.*, 2000). This may have an effect on economic development

throughout the world. With a larger proportion of populations being retired or no longer of an age to work, this leaves a smaller work force to develop the economy. However, this often represents only percentages and not total number, thus even if there is pronounced aging, there may still be an adequate labour force available, especially as female participation rates increase. It still remains that the most important characteristic of the work force is not the number of participants, but qualitative factors like education; these characteristics ensure continuous development and growth of economies in the long-term through constant productivity.

As well as population and demographics, social change and development is important in encouraging economic growth. Advances in technology, for instance, often require a social acceptance that enables discoveries and innovations to move forward and be implemented. Barro & Sala-i-Martin (2004) have highlighted the relationship between economic growth and law enforcement; they argue that legal rights and democracy are necessary for markets to be successful and enhance growth. Of course it is difficult to quantify such social issues in terms of monetary value or other such indicators, however, these factors must be taken into account in different scenarios. Through the use of the 'storylines' the SRES was able to set frameworks that describe social and cultural variations explicitly.

International trade is often thought of as encouraging economic gains. Globalisation offers opportunities for liberalised markets and the flow of information and capital throughout the world. However, it is the improvement of technology that drives forward growth in productivity and increases economic value (Barro & Sala-i-Martin, 2004). Indeed, GDP grew by 63% between 1947 and 1973 in the OECD countries as a result of technological change and advancement (Barro & Sala-i-Martin, 2004). This growth rate slowed down beyond the 1970s as the OECD moved beyond industrialisation to a service orientated economy.

It was suggested by Nakicenovic *et al.* (2000) from empirical evidence that energy and material intensities are closely related to macroeconomic productivity. This implies that high GDP per capita is associated with lower energy and materials intensities. The SRES utilised this relationship where overall economic productivity growth and reductions in energy use per GDP are well linked.

Uncertainties in population growth rates tend to narrow the range of associated gross world product projections (Nakicenovic *et al.*, 2000). It is often assumed that high population growth is associated with low per capita economic growth whilst low population growth has the opposite effect. Those countries in the high per capita income group tend to have completed their demographic transition; they also have long life expectancies and generally have smaller families with fewer children (Nakicenovic *et al.*, 2000).

6.4.2 Economic Growth Scenarios

The SRES scenarios cover a large range of possible economic developments up to 2100. In contrast to the population projections, there are no long-term trajectories for economic development. Indeed, a long-term projection is often assumed to span only 10 years. Thus the IPCC developed scenarios as exogenous input assumptions (Nakicenovic *et al.*, 2000).

The A1 storyline represents the highest growth rates, followed by the B1 scenario family, both representing various options to slowly close the income gap between regions. The A2 and B2 scenarios are shown to be the lowest two storylines, with less focus upon globalisation. The future GDP levels have been discussed as being dependent upon population growth and technology and productivity developments. There was a large amount of uncertainty for per capita GDP growth, resulting in a range of growth rates from 0.8 to 2.8% per year for the 1990-2100 period (Nakicenovic *et al.*, 2000). These uncertainties were magnified when regional disaggregations were applied.

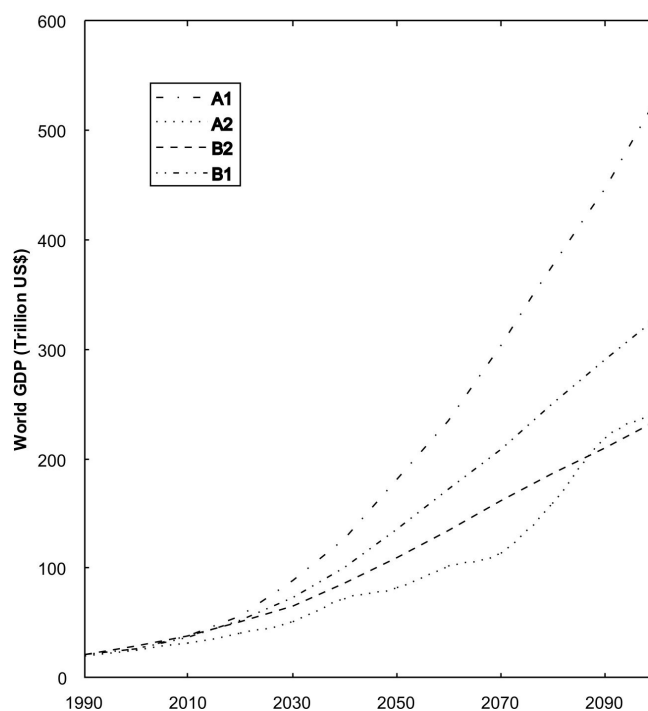


Figure 6-2: Global GDP projections for four SRES marker scenarios

The scenario family A1 has a high growth pattern due to the rapid demographic transition, access to knowledge for all regions of the world and advanced technologies, social and political systems (the marker scenario is highlighted in Figure 6-2). The A2 family has a slower productivity growth rate and subsequent incomes. This is caused by the slow demographic changes and fragmented economic developments, with slow convergence among regions. There is substantial economic growth in the B1 worlds – Figure 6-2 shows the B1 marker scenario only – but this is achieved and treated in a

different manner to the A1 storyline. The B1 world has strong environmental protectionism as well as a good level of social consciousness and the reduction of income inequalities is a result of both international and domestic endeavours. The B2 scenarios have a medium economic growth rate (the marker scenario is shown in Figure 6-2); the global population is stabilised and there is a sustained, if not booming, level of development that cause this storyline to follow a middle ground. There remains some disparity between income groups, but no where near as significant or defined as in the A2 situation.

6.5 ENERGY AND LAND USE

Energy use and emissions are frequently represented in terms of major end-use sectors. There are significant differences between sectors and also between regions of the world. Industry is a key sector, as well as transportation, commercial and residential communities. There are a variety of drivers for energy use, which include economic drivers, energy intensities, population size and urbanisation. These factors are individually driven by consumer choice, energy costs, technical progress, infrastructure, and of course economic conditions.

Primary energy use is continually growing, at an average growth rate of 2.5% per year (Nakicenovic *et al.*, 2000). Industry is the most dominant sector holding 42% of global primary energy in 1990, followed by the building sector with 34% in the same year, the transport and agriculture sectors follow with 21% and 3% respectively. The energy use in the industrial sector is mainly contributed to by energy-intensive products, such as steel, paper and cement. Countries undergoing rapid industrialisation tend to have high demands for these commodities. In 1990, the industrialised countries dominated the industrial sector, representing 42% of the primary energy, higher than the 29% of the REF region of the world and 20% and 9% for the ASIA and ALM countries (Nakicenovic *et al.*, 2000) (See Appendix B for definition of these regions).

Carbon emissions resulting from energy use are dependent upon the carbon intensity of the energy source (Nakicenovic *et al.*, 2000). The carbon intensity changes according to different fuel substitutions, as well as advances in technology and processes. There was a move towards less carbon intensive fuel among the highly industrialised countries between 1971 and 1992 (Ang & Pandiyan, 1997; Schipper *et al.*, 1997). Emissions were indeed increasing, but at a slower rate than the growth in economies for the OECD (Schipper *et al.*, 1997). The resultant decrease in energy intensities implied a move from coal and oil, as well as a marked reduction in energy-intensive manufacturing. This is not the case for some of the industrialising countries, for example China, where there is still high dependency upon coal for energy. However, some developing countries have been able to make the move away from dirty fuels to alternative fuel types; South American nations, for example, are heavily dependent upon hydropower. Carbon intensities in the industrialised sector have also been fairly stable among rapidly

developing and industrialising regions, this is as a result of reduced energy intensity, developing economies and changing carbon intensity in the fuel mix.

Energy intensity can be improved with the progression of technology and efficient, energy saving techniques. This is the case in many industries, such as transportation, manufacturing and construction. Lovins (1996) suggests various improvements that can be undertaken, stating that it is often cheaper to make large improvements than to make only small developments (Lovins, 1996). Major improvements are often realised in a relatively short time-span, between 10 and 15 years.

Buildings have high levels of energy use. The intensity of energy use is driven by determinants such as population, dwelling size, number of residents and commercial floor space. As nations move towards urbanisation, there is an increase in energy supply demands for lighting, heating/cooling and refrigeration. Energy consumption is strongly correlated to income levels (Nakicenovic *et al.*, 2000), therefore industrialised countries tend to have higher consumption levels due to the increased number of appliances, more services and larger homes. Space heating is an important end-use for many of the industrialised countries; however it is less common in most of the developing countries, with the exception of China where heating accounts for half of the residential and commercial building energy demand. In the developing world, cooking and water heating dominate the energy use in buildings.

Transportation clearly has a high energy contribution, and is continuously growing. The industrialised world has the larger proportion of global transportation primary energy, using 62% percent in 1990, with the REF, ALM and ASIA regions having a 16%, 12% and 10% share respectively (Nakicenovic *et al.*, 2000). Despite the ASIA region having the smallest percentage share, it sees the most rapid growth per year, 5.9% (Nakicenovic *et al.*, 2000). Factors that affect transportation emissions include travel activity, energy efficiency and other technological advances such as carbon intensity improvements. Travel is currently related to economic activity, settlement patterns and price of fuel. Future developments in telecommunications may change the way that we travel, so that people no longer have to travel to work but can facilitate home-working. The internet also plays an important role in reducing travel needs, for example online shopping permits people to make purchases without needing to travel to stores.

6.5.1 Energy and Land Use Scenarios

The scenarios were created to illustrate the difference that energy and land use will have upon GHG emission as the future unfolds. The A1 and B1 scenario groups assumed a transition towards more non-fossil energy in the future, whilst B2 scenarios have a more moderate transition with half of the energy being produced by non-fossil sources and the other half consisting of coal, oil and gas. The A2 scenario group represents a complete regression back towards coal, with small increases in the use of non-fossil fuels and a decrease in oil and gas usage (Nakicenovic *et al.*, 2000).

In terms of land use, the main driving forces were considered to be the growing demand for food due to expanding populations and changing diets. For many of the scenarios, forest loss is reduced as a result of decreasing population growth and increased agricultural productivity (Nakicenovic *et al.*, 2000). This is most prominent in the A1 and B1 scenario families. Other social and economic factors also play a part, such as deforestation, expansion of cropland and reforestation. Indeed the B1 scenarios see a decrease in pasture land, caused by a move away from meat based diets, resulting in less deforestation (Nakicenovic *et al.*, 2000).

6.6 TECHNOLOGICAL IMPROVEMENTS

The world is becoming more and more technologically advanced. This is enabling the planet to be more inter-connected, more efficient and more productive. It can be argued that the footprint will benefit by the growth of technology, as energy efficiency is improved and yield rates are increased through for example, better farming techniques. However, developments in technology can also cause negative rebound effects. A paradigm may be the motor industry: vehicles are becoming more efficient and emit fewer emissions, however they are also more affordable and available, causing incentives for purchases. As a result there is a booming number of cars populating our roads. Be it a positive or a negative effect, technology was thought to be highly influential upon national ecological footprints and hence was included within the analysis undertaken in Chapter 8.

Technological innovation in the agricultural sector may lead to increased cereal yields per hectare of land used (by using fertilisers that affect the harvest) and increased yields from livestock (by enhanced feed and heating), although energy resources would be required to achieve this. The availability and use of global cropland area rose by less than 10% in the period 1961-1999, despite the population doubling (Environmental Assessment Institute, 2002). In the WWF *Living Planet Report 2002* it was suggested that this was made possible through developments in irrigation, the use of fertilisers, and what was termed 'technological progress' (WWF International, 2002). Thus, it is possible that cropland productivity may be able to keep pace with the growing population. If the 'world farmer' were able to reach the average yield of today's US corn grower, then ten billion people (above the United Nations mean population forecast for 2100) would only need around half of the present cropland, yet they could consume today's US calorie intake (Ausabel, 2000). Consuming at the rate and level of the average American may not be advisable, but this relationship implies that with advancement in farming methods, such as irrigation and fertiliser use, future cropland area might only require minimal growth. Nevertheless, there is clearly an issue around the disconnect between regions of agricultural production and those where humans consume food. These would need to be balanced by developments in food preservation, storage and long-distance transportation.

6.7 GHG EMISSIONS

The SRES scenarios covers a full range of GHG emissions as well as sulphur emissions. Land use change contributes to GHG emissions. Activities include deforestation, afforestation and changes in agricultural management. The largest contribution to global emissions is made to CH₄ and N₂O, whilst it is relatively small for CO₂ (23%) (Nakicenovic *et al.*, 2000). Despite this small percentage of global CO₂ emissions attributed to land use change, such changes contribute significantly to the CO₂ emission in developing countries, up to 45% (Nakicenovic *et al.*, 2000). Therefore changes in land use are relevant when estimating climate change and deciding mitigation strategies.

Deforestation is one of the main factors that effect sequestration of anthropogenic CO₂. Thus emissions of CO₂ tend to occur from the burning of forests and clearing of vegetation, for agricultural purposes for example. The developing regions of the world tend to have more significant deforestation than the industrialised nations, take the devastation of the Amazon rainforest for instance.

Carbon dioxide emissions were assumed to be driven by population, economic wealth and primary energy requirements within the SRES. An increase in any of these factors was considered to have an impact growth in emissions. Interestingly, alternative combinations of these driving forces were able to lead to similar levels of GHG emissions (Nakicenovic *et al.*, 2000). On the other hand, the changes in socio-economic developments could cause very large differences in GHG emissions, due to the use and advancement of technology. This highlights the importance of technology as a driver affecting GHG emissions.

6.7.1 Carbon Emissions Scenarios

The rise in carbon dioxide emissions into the future is extremely large; the highest level reaches ten times that of today's emission by 2100, whilst other scenarios show a reduction to levels below today. Scenarios are classified within the 'intervention', 'non-intervention' and 'non-classified' categories, which identifies those that include climate incentives, those that do not and those that cannot be given to the other categories (see Figure 6-3). The four scenario families are illustrated in Figure 6-3 by the coloured vertical lines, as well as the marker scenarios (thick coloured dotted curves). Figure 6-3 illustrates that most of the global range of energy-related carbon dioxide emissions based upon the literature is covered by the SRES scenarios. The dashed lines depict individual SRES scenarios and the blue shaded area indicates the range of scenarios from the literature. It is only the most extreme situations that were not included within the SRES scenarios, visible at the tails of the distribution.

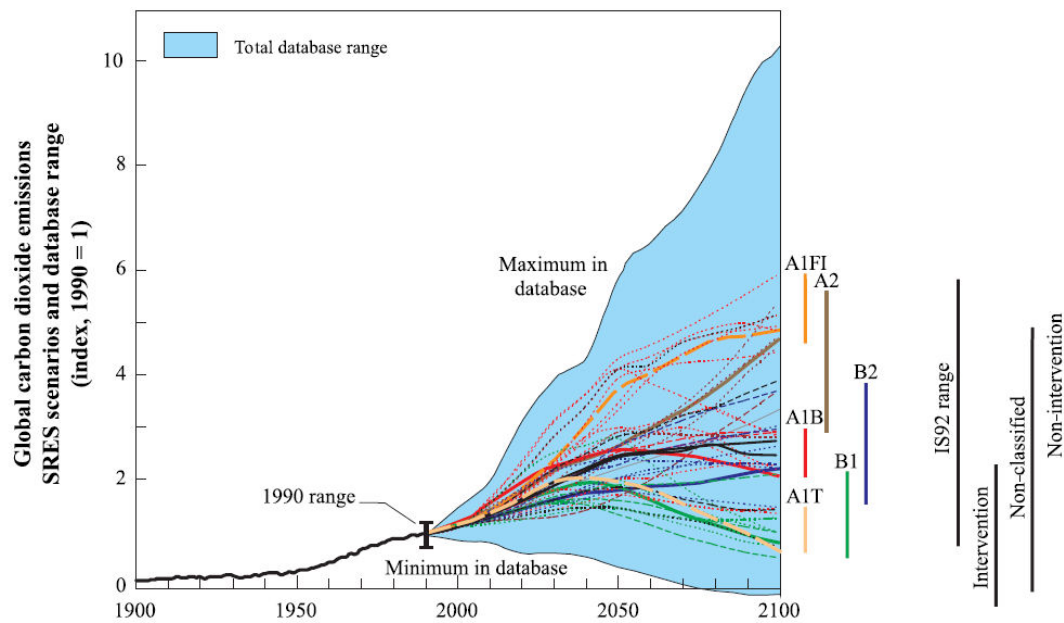


Figure 6-3: Global CO₂ emissions from energy and industry –

Historical development from 1900 to 1990 and 40 SRES scenarios from 1990 to 2100, shown as an index (1990 = 1). The dashed time-paths depict individual SRES scenarios and the blue shaded area the range of scenarios from the literature. The median (50th), 5th, and 95th percentiles of the frequency distribution are shown. The coloured vertical bars indicate the range of the four SRES scenario families in 2100. Also shown as vertical bars on the right are the ranges of emissions in 2100 of IS92 scenarios and of scenarios from the literature that apparently include additional climate initiatives (designated as "intervention" scenarios emissions range), those that do not ("non-intervention"), and those that cannot be assigned to either of these two categories ("non-classified").

Source: Nakicenovic *et al.* (2000)

The four scenario families satisfactorily cover a large part of the range each. This implies that a large range of emissions may result from scenarios with similar quantifications. This shows that there are too many uncertainties to be able to give a unique set of future emissions for a given set of driving forces. There is also much overlap in future emissions between the four scenario families. This means that different scenarios following quite different pathways can result in a similar final emissions value. The A1B and B2 marker scenarios are an excellent example, with final emissions of 13.5 and 13.7 GtC in 2100 respectively. These results cannot be taken without some understanding of both of the scenarios, since the dynamics of their pathways are considerably different; this may be represented by the cumulative carbon emissions, which offers an alternative illustration of the scenarios. This is important when analysing the results in terms of impacts on the climate and suitable mitigation strategies.

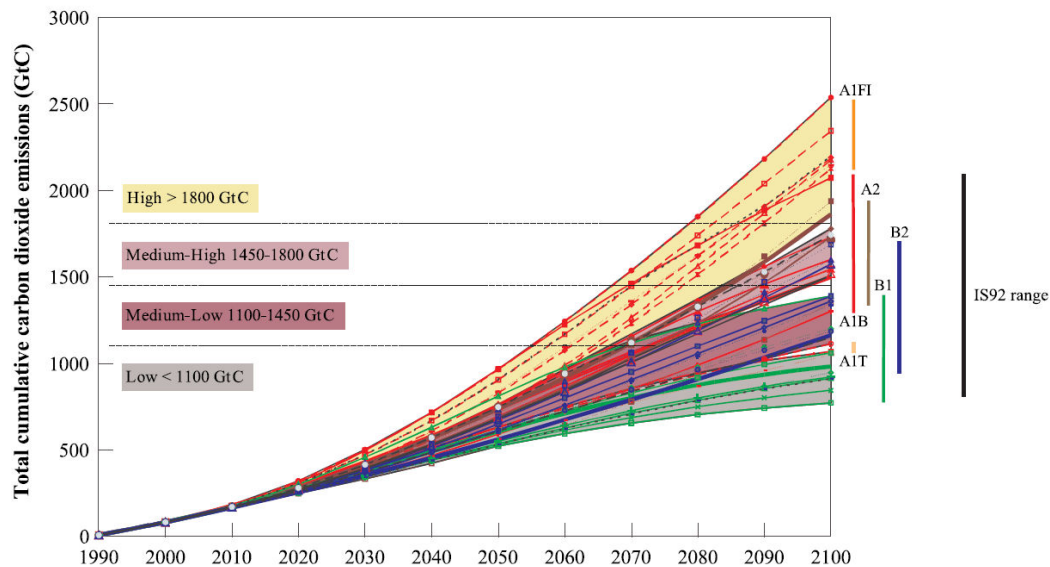


Figure 6-4: Global cumulative CO₂ emissions (GtC, standardised)

The ranges of cumulative emissions for the SRES scenarios are shown. Scenarios are grouped into four categories: low, medium-low, medium-high, and high emissions. The ranges of cumulative emissions of the six SRES scenario groups are shown as coloured vertical bars and the range of the IS92 scenarios as a black vertical bar.

Source: Nakicenovic *et al.* (2000)

Many of the scenarios in the SRES showed reductions in carbon emissions by the end of the 21st century. However, by considering the cumulative carbon emissions, the scenarios which had best overall reduction in emissions during the time period could be analysed (Figure 6-4). This offers a large amount of scope in the assessment of climate change impacts, mitigation and adaptation strategies. By contrasting these cumulative emissions with the total emission in 2100, it was shown that some future worlds that have fundamentally different characteristic features can have very different cumulative emissions despite having a similar final carbon emission value in 2100.

It was expected that future changes in carbon emissions would result primarily from total energy consumption and the structure of energy supply (Nakicenovic *et al.*, 2000). The rapid growth in the economy associated with the A1 storyline was assumed to create a large energy demand and consequently cause high levels of carbon dioxide emissions. In this scenario family the initial CO₂ emissions increase until 2050 when structural changes in the energy sector begin to have an effect, resulting in a decrease in carbon intensity. This is able to offset the growing energy requirements from a prosperous world with a decreasing population. The A2 scenario family has been depicted as having slow development rates in technologies, and dependence upon fossil fuels therefore remains; as such the carbon emissions continue to grow with little tendency to decrease. The environmentally aware world of the B1 storyline offers structural change towards less energy intensive activities and provides developments for resource saving and efficient technologies. These solutions are rapidly advanced and implemented throughout the regions of the world. The resultant emissions

consequently peak and decrease to below base-year levels by the end of the century. The B2 scenario family represents an environmentally conscious, but heterogeneous world. Populations and economies tend to grow, causing a steady increase in carbon emissions.

6.8 CLIMATIC AND GEOGRAPHICAL FACTORS

Climatic factors, such as precipitation and temperature, were considered as potentially significant influences on national ecological footprints. It postulated that the temperature profile across arable land would, for example, have an impact on food productivity. Hot and cold climatic extremes within different regions of the world are likely to result in reduced productivity, as is the case in parts of the Russian Federation. The temperature across habitable areas could also influence the energy use of a nation, particularly for space heating or cooling. Northern Europe uses more energy for heating than do warmer climates, such as central Africa. However, wealthier countries with large temperature extremes, like the USA, may also have higher energy consumption in the summer and winter, than spring and autumn, due to the use of air-conditioning and heating respectively during climate extremes.

The rainfall (precipitation) experienced by a nation could be cross-correlated with crop yields within the model. Soil fertility is likely to influence the crop yield of biologically productive land in much the same way as temperature and precipitation. Indeed, humanity is dependent upon soil as a resource for food, fuel, and fibre (UNESCO & IUBS, 1991). Terrain was assumed to be another factor that could affect national ecological footprints.

6.9 OTHER FACTORS AFFECTING GHG EMISSIONS

Population, economic wealth, technology have all been discussed in relation to their correlation with GHG emissions. These can all be measured quantitatively and assessed successfully within different scenarios. There are other factors that also affect the emission of GHGs and help to shape various scenarios. These are far more qualitative, and tend to be policy based. The obvious policies to reduce emissions would be those related to energy, however, within the scenarios there are far more options, including economic development, technological change, education, industry, health, and agriculture.

Population policies can be developed to control social welfare and normalise population growth. Fertility rates can be changed, as can the health and education of different demographics. For example, women can be educated in contraception and family planning can be made readily available for those who want or indeed need it. Young girls can be sent to schools, which as well as improving education among the young, provides better gender equality and empowers women to better their life opportunities.

In terms of economic growth, governments have the capabilities to encourage development within particular industrial sectors. As such they can support energy efficient technologies and sectors that are less fossil-fuel intensive. Of course, governments and decision makers will be driven by policies that ensure the development and growth of their economies, and this may not always be in line with environmental protectionism.

It is difficult to implement policies into the scenarios of the SRES, since the impacts of each policy is uncertain. For this reason the storylines were adopted to give a broad scope of different policies that affect certain environmental, economic and technical outcomes.

6.10 SUMMARY

A selection of analysis techniques were utilised within this thesis, namely dimensional analysis and multi-linear regression. Both of these techniques enable analysis behind which of a host of variables most significantly influence the *per capita* carbon and ecological footprint. For both analytical methods all variables must be independent, such that there is no cross-correlation within the final equations. The resulting 'power-law' equations therefore describe the relationship between the footprints and a reduced selection of factors.

The analyses undertaken within this thesis have been highlighted by identifying individual countries, based upon the G8+5 and G-20, as well as the two regions of the world: the affluent North and the populous South. This enabled the results to be scrutinised with respect to individual country situations and to compare and contrast key differences between the major regions.

There are many driving forces for the footprint and related scenarios; here those attributed to the IPAT equation have been discussed alongside other important variables: population, economic wealth, energy use, technology, GHG emissions and climatic variation. Many of these factors are interlinked and vary across different regions of the world, and they will change significantly as humanity develops and progresses into the future.

CHAPTER 7

ANALYSIS TECHNIQUES AND NATION STATE SELECTION

7.1 INTRODUCTION

A variety of analysis techniques were applied throughout this thesis. Dimensional analysis and multi-linear regression were utilised to assess the significance of a range of determinants and their effects upon the footprint. These techniques are introduced and discussed in this chapter.

An assortment of different nation states have been identified and subsequently scrutinised with regard to the each study (Chapters 8-11), to include a spectrum of industrialised, transitional and developing countries. The selection of countries and global regions that are applied in this thesis are detailed here.

7.2 ANALYSING DETERMINANTS OF THE FOOTPRINT

A variety of driving forces behind the footprint has been established in Chapter 6. Two techniques were adopted to analyse the correlating 'power-law' equation and the individual relationships between the determinants and the national *per capita* footprint, as well as with each other. Assessment was made for both the ecological footprint and carbon footprint, detailed in Chapter 8 and Chapter 9. Dimensional analysis was applied, using graphical representation of the data, to find the initial results. This was cross-checked using multi-linear regression techniques to ensure no errors were made and to prove the compatibility of the determinants with the footprint.

7.2.1 Dimensional Analysis

Dimensional analysis is a method by which information is deduced about a phenomenon from the single premise that the particular phenomenon can be described by a dimensionally correct equation among certain variables (Langhaar, 1951). This type of analysis is commonly used in many fields of engineering, particularly in heat-transfer and fluid mechanics. Dimensional analysis is a highly useful technique, whereby a variety of factors are considered with relation to one dependent parameter. The disadvantage is that it is not always easy to understand the inner mechanism of the phenomenon being scrutinised without having further understanding of the subject.

In order to apply dimensional analysis to any phenomenon, the assumption must be made that certain named variables are totally independent of each other; all others are redundant or irrelevant. The first stage of determining and naming the variables often requires cognitive insight into the phenomenon being assessed. When formulating

mathematical formulae, often the governing parameters are unknown, and must be chosen on the basis of a qualitative model of the trend, which the investigator must determine using previous experience and knowledge (Pankhurst, 1964). This was undertaken in the case of the determinants for national footprints, as discussed in Chapter 8 and 9.

The plausibility of derived equations is routinely assessed by employing dimensional analysis. It is commonly used in mathematics and the sciences to assess the properties of variables independent of their units. Dimensional analysis can also be adopted to derive relationships between the physical quantities that are involved in a specific phenomenon, such as the ecological footprint. One such example is when Lord Rayleigh attempted to understand why the sky is blue in 1872, and applied dimensional analysis techniques to complete his analysis (Pesic, 2005). Lord Rayleigh considered the dimensions of this unknown quantity in order to better understand its proportionality to different factors upon which it depends. The analysis revealed the basic law governing the scattering of light, such that 'the brightness of scattered light from small particles falls off as the fourth power of the wavelength of the light' (Pesic, 2005). This explains that light with a longer wavelength will be scattered less than those with shorter wavelengths, thus red light is scattered less than blue light with wavelengths of 650 nanometres and 400 nanometres respectively. This is an excellent example of the power and usefulness of dimensional analysis.

Dimensional analysis is based upon dimensional homogeneity. This deals not only with simple applications but also considers the formulation of dimensionless products and their role in model-scale testing, deducting suitable scale factors and the conditions where such factors may be used without making further assumptions (Pankhurst, 1964). The principle of dimensional homogeneity states that physically meaningful algebraic expressions are dimensionally consistent, that is all the parameters are expressible as the same combination of physical dimensions. All physical quantities can be measured using a standard set of dimensions – mass, length, time, electric charge, and temperature – these are simply combined into sets of units. For example, velocity uses both mass and time measured in a variety of units: metres per second, miles per hour, knots. By disaggregating the dimensions it is possible to assess the fundamental properties of the system or equation being analysed.

The homogeneity principle can be applied to determine the powers by which any quantity occurring in an analytical expression must be raised (Barenblatt, 1987; Barenblatt, 1996; Pankhurst, 1964).

7.2.1.1 *Formulating an equation*

In many studies, attempts are made to obtain relationships between quantities that define a particular phenomenon (Barenblatt, 1987). Such problems require the reduction of relationships of the form:

$$x = f(x_1, x_2, \dots, x_n) \quad 7-1$$

where x is the parameter being examined, and x_1, x_2, \dots, x_n are the governing parameters, of which there may be many.

The dimensional function for any physical quantity is always expressed as a 'power-law' (Barenblatt, 1996). Thus the dimension of the quantity ' x ' to be established must be expressed as products of the powers of the dimensions for the parameters:

$$[x] = [x_1]^a [x_2]^b \dots [x_n]^y \quad 7-2$$

As such the governing variables must be independent. The use of dimensions in this way is often applied to ensure that equations measuring physical quantities are dimensionally homogeneous. The physical dimensions of a physical quantity is an expression showing the dependence of the proper unit of that quantity on the fundamental units (Duncan, 1953). Non-dimensional quantities are still functionally related; examples include the Reynolds number, a commonly used non-dimensional parameter. Appendix C gives a worked example to further illustrate the functionality of dimensional analysis.

7.2.1.2 Application

Using dimensional analysis tends to result in a reduced form of an initially postulated equation; since often some parameters are proven to be insignificant or redundant (they return exponents of approximately zero). This is therefore a very useful mathematical tool for experimental scientists who do not wish to collect unnecessary data for many variables when it may not be required.

Applying this analytical technique for the ecological footprint is valid, even though the footprint and some of its parameters are not tangible physical quantities. Since this type of analysis is frequently used to determine the relationships between variables and dependent factors, in this case the footprint, it was considered a suitable technique to adopt. This type of analysis has only been undertaken once before with respect to ecological footprints by Hammond (2006a); this is considerably developed within this thesis looking at far more detailed determinants not only for the ecological footprint, but also the carbon footprint.

Dimensional analysis was applied to refine the correlating 'power-law' equation which contained many different parameters, as detailed in Chapter 8 and 9. Using this technique also ensured that there were no interdependencies or cross-correlations between the variables. The dimensions associated with the 'power-law' equation may not be homogenous, and indeed many do not represent units commonly seen in the

sciences (\$ per capita, for example). The constant in the resulting 'power-law' correlation effectively includes a unit converter that ensures the equation satisfies the so-called 'principle of homogeneity of dimensions' (Duncan, 1953).

7.2.2 Multi-linear Regression

The studies undertaken using dimensional analysis were verified using multi-linear regression. In the same way as dimensional analysis, this technique was able to assess and determine an expression representing the relationship between many variables and a dependent parameter.

Linear regression represents a model showing a relationship between independent and dependent variables. It is commonly used in terms of a 'least-square' fit, which can fit both lines and polynomials. Multi-linear regression allows a set of simultaneous equation to be constructed and solved by forming a design matrix and solving for the parameters. This relationship is useful for understanding which variables have the greatest effect.

In multi-linear regression there are several independent variables. Such a regression technique presumes that there is only one dependent parameter (for example, the ecological footprint (*ef*)), which is influenced by several independent variables (for instance, GNI).

With Multilinear Regression it is assumed that the dependent data, *y*, depends linearly on several independent variables, $x_1, x_2, x_3, \dots, x_i$. As such *y* represents the ecological footprint, *ef*, and x_i represents the independent factors (carbon ratio, for example).

A set of simultaneous equations were solved by forming a design matrix and solving for the parameters. The calculated linear equations were in the form:

$$y = a_0 + a_1x_1 + a_2x_2 \quad 7-3$$

where a_0 is the constant, and a_1 and a_2 are the values being solved for. These are clearly not powers and therefore not comparable to the results in dimensional analysis and the 'power-law' equation. To account for the exponents in the 'power-law' equation, the expression above was re-written using logs:

$$\ln y = \ln a_0 + a_1 \ln x_1 + a_2 \ln x_2 \quad 7-4$$

such that the final equation would identify the exponents:

$$y = a_0 \cdot x_1^{a_1} \cdot x_2^{a_2} \quad 7-5$$

To validate the model, the maximum of the absolute value of the deviation of the data from the model was determined. This value had to be much smaller than any of the data values, in order to indicate that the model accurately follows the data.

It was first necessary to establish whether a relationship exists between pairs of quantities. Thus a linear correlation analysis was performed for all of the parameters. These results were similar to those returned from the Excel dimensional analysis. Multi-linear regression was subsequently employed to assess the correlation of the remaining parameters. This ensured that the dimensional analysis was cross-examined for the suitability of the correlation.

7.3 FOCUS UPON INDIVIDUAL NATION STATES AND REGIONS OF THE WORLD

A variety of groups of nation states have been considered throughout this thesis. The boundaries have been set to follow the so called groupings of the majority South and prosperous North. These have been specifically discussed within certain chapters (Table 7-1), highlighting direct differences between these regions of the world historically, currently and into the future. Individual countries have also been considered, and these groupings have developed throughout the work to keep in line with international negotiations and UN discussions. As such the G8 + 5 are initially examined, but as more nations join the debate surrounding climate change and the G-20 unit came to the forefront of the public eye and media attention, this grouping was scrutinised.

Chapter	Regions of the world and countries under scrutiny
Chapter 8	G8 + 5
Chapter 9	G20
Chapter 10	Developing and industrialised nation states
Chapter 11	Developing and industrialised nation states

Table 7-1: Nations under scrutiny within each chapter

7.3.1 The Prosperous North and the Populous South

It is important for developed, or industrialised countries (in the prosperous North) to play their full part in maintaining environmental sustainability as they currently emit the bulk of carbon dioxide (CO₂) and other gaseous pollutants into the atmosphere (Hammond, 2000). But sustainable development must also be viewed in a global context. The task facing the nearly 80% of the world's population that live in developing countries (the majority South) is daunting. The countries that make up these two regions of the world are depicted on the global map shown in Figure 7-1.



Figure 7-1: The global north-south divide

[The industrialised North - black; the populous or majority South - white with black edging].

It can be seen there that Australasia (Australia and New Zealand) are 'honorary' member countries of the North. The South has, in most cases, rapidly growing populations that will drive up energy consumption and environmental pollution. This will feed back to the whole planet, and thereby alter the climate experienced by the wealthier nations. Consequently, the South needs assistance from these industrial countries in order to promote their economic growth (which will, in time, induce a "demographic transition" (Hammond, 2000)) and to improve the efficiency of their energy systems. Collectively, the developing countries have a large population, with 80% of the human population. This region of the world is consequently sometimes referred to as the 'majority' South, whilst the affluent North is highlighted as the 'prosperous' North. The breakdown is shown in Table 7-2.

Developing South	Industrialised North
<p>Africa</p> <p>Central America, South America, and the Caribbean Nations</p> <p>Centrally Planned Asia</p> <p>Far East</p> <p>Middle East</p> <p>Oceania (minus Australia, Japan and New Zealand)</p>	<p>Centrally Planned Europe (Eastern Europe)</p> <p>North America</p> <p>Western Europe</p> <p>Australia, Japan and New Zealand</p>

Table 7-2: Breakdown of nation states in the Developing South and Industrialised North

7.3.2 G8+5 Nation States

Particular focus has been made upon the G8 + 5 group of nations in Chapter 8. The G8 + 5 group includes the industrialised (mainly 'high income') countries [Canada, France, Germany, Italy, Japan, the Russian Federation, the United Kingdom (UK), and the United States of America (USA)] – the G8 – plus five of the largest 'emerging' (mainly 'middle income') economies of the developing world: Brazil, the People's Republic of China (PRC), India, Mexico, and South Africa (see Figure 7-2). They are viewed as being a stronger and more representative grouping than the G8 alone. When the G8 + 5 group were formed in 2005, it was hoped that they would provide fresh stimulus for the so-called Doha Round of international trade talks, and revitalised co-operation aimed at the climate change mitigation.

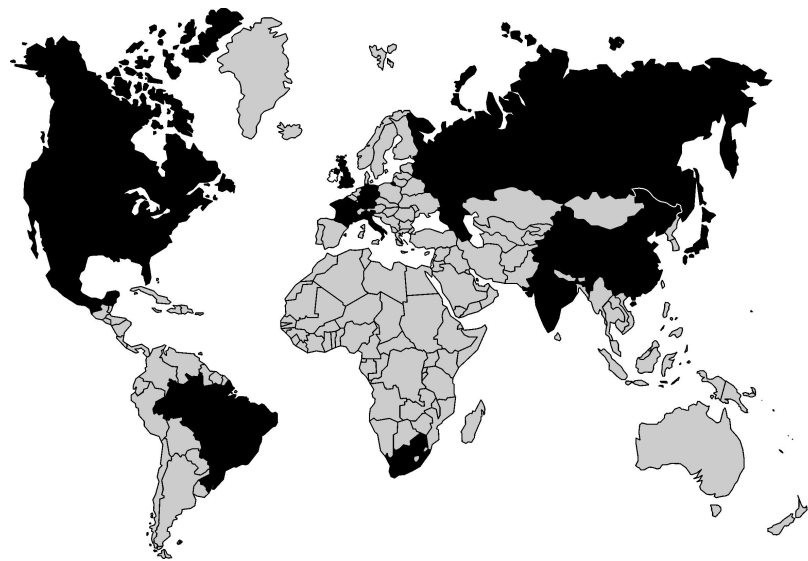


Figure 7-2: The G8 + 5 group of countries superimposed on the world map

[The G8 nations (l → r) USA, Canada, France, UK, Germany, Italy, Russia, and Japan; the five large emerging economies (l → r) Mexico, Brazil, South Africa, India and China].

The G8 industrialised nations are located in the geographic North of the planet (see again Figure 7-2), whereas the five emerging economies are situated in the populous, or 'majority' South, accommodating about 80% of the human population. Thus, the G8 + 5 grouping was seen as providing a new paradigm of future international co-operation. A process of permanent dialogue between the G8 + 5 nations was fully institutionalised in 2007 under the Heiligendamm process: named after the German town where it was agreed. In light of the world financial 'credit crunch' of 2008-2009, the programme for the G8 + 5 nations has concentrated on the impact of the consequent economic downturn in the context of the key challenges arising from energy security, global warming, land use change, and population growth projected to rise by a further 3 billion (to around 9 billion people worldwide) over the 21st Century (Cranston *et al.*, 2010).

7.3.3 G-20

The G-20 has been highlighted in Chapter 9 to illustrate differences in the developing South and industrialised North (Figure 7-3), with particular focus on those developed and transitional countries that are able to make a stand and implement change regarding moving toward sustainable development. The G-20 is represented by 19 finance ministers and central bank governors of 19 countries and the European Union. It aims to bring together industrialised and developing countries from around the world to discuss important global economic issues. These 19 countries are particularly significant as they represent approximately 80% of the world's trade and two-thirds of the global population. The G-20 grew in status following the 2008 Washington summit, where it was announced that this grouping would replace the G8 as the main economic council of wealthy nations, including a more representative unit across the globe. Countries are representative of all continents with the exception of Antarctica (Table 7-3).

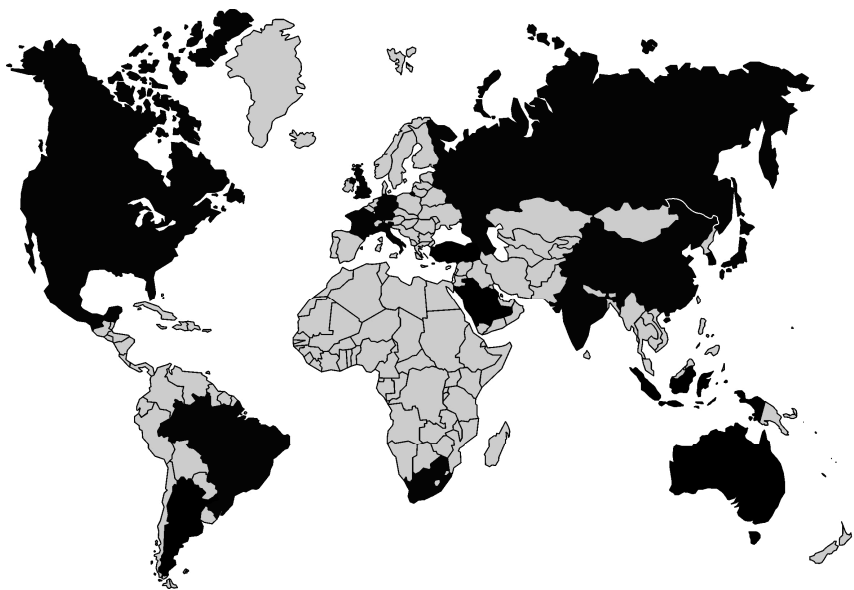


Figure 7-3: The G-20 grouping of nations identified on the world map

[(l → r) USA, Canada, Mexico, Argentina, Brazil, France, UK, Germany, Italy, South Africa, Russia, Turkey, Saudi Arabia, India, China, Indonesia, South Korea, Japan, and Australia]

Continent	G-20 Member
Africa	South Africa
South America	Argentina Brazil Mexico
Northern America	Canada United States of America
East and Southeast Asia	China Japan South Korea Indonesia
South Asia	India
Middle East	Saudi Arabia Turkey
Europe	European Union France Germany Italy Russia United Kingdom
Oceania	Australia

Table 7-3: G-20 Membership

CHAPTER 8

EXPLORING FACTORS THAT AFFECT NATIONAL FOOTPRINTS

8.1 INTRODUCTION

Footprints vary between countries at different stages of economic development and varying geographic characteristics (Hammond, 2006a; Hammond, 2006b). The ecological footprint has been considered to be dependent on an assortment of parameters, varying from population growth to economic wellbeing to climatic factors (see Chapter 6). The significance of four such variables has previously been investigated by Hammond (2006a). A correlating equation was developed to express the relationship between the *per capita* national ecological footprint and a selection of independent variables. Hammond (2006a) originally postulated that *per capita* national ecological footprints might be a function of a range of four variables: population density, national income, energy intensity and carbon emissions. He correlated these parameters based on international data for the turn of the millennium (that is approximately 1999-2000) for a dataset of 113 nation states. The resulting 'power-law' expression, derived using 'dimensional analysis' techniques (see Chapter 7 for details) widely used in engineering and the physical sciences, indicated the relative significance of these factors. Hammond (2006a) demonstrated that *per capita* national ecological footprints were strongly dependent on per capita national income and only weakly on population density at the turn of the millennium.

It has been recognised that a far larger array of determinants affect the footprint and have an influence on the makeup of footprint in a variety of unique ways, as discussed in Chapter 6. Detailed research regarding individual driving forces for the footprint is rare. Through careful analysis of these factors, the footprint can be further understood in terms of the fundamental determinants influencing its size and shape. Hammond's analysis was therefore re-examined employing a much wider range of possible dependent variables and more recent datasets, including not only those previously evaluated by Hammond, but also a selection of other atmospheric, terrain based and technological factors, thus expanding this study far beyond the boundaries of the IPAT equation. The work described within this chapter follows the same use of the 'power-law' equation as Hammond, but its original contribution is the development of this equation to include a far larger range of variables utilising more recent datasets. These results are discussed here as well as in the paper published by Cranston *et al.* (2010).

Ecological footprints for developed and developing countries from around the world were analysed. Footprint data produced for the World Wide Fund for Nature (WWF) in their *Living Planet Report 2006* (WWF International, 2006) were utilised, along with a

wide variety of other international datasets available for the year 2003. The determinants of these ecological footprints were evaluated using scaling arguments, cross-checked via multi-linear regression. An aggregate data set for 109 countries was established from these various databases that provided statistical indicators of *per capita* ecological footprints, population size, land area, national income, energy use, carbon emissions, soil fertility and climatic factors, terrain, and latitude. National climates were represented in terms of average temperatures and precipitation.

Variations about the resulting 'power-law' correlation suggest the extent to which individual nation states are currently frugal or profligate in terms of their resource use and environmental impacts. They highlight the need to live within the biocapacity of the planet in order to achieve what is often termed as 'sustainable development'. The underlying relations within the North-South environmental and development nexus were discussed.

This chapter details the development of a correlating 'power-law' equation in order to achieve Objective 5, such that key determinants are analysed to establish a relationship between the *per capita* ecological footprint and a host of variables. This will bring about results for Aim 1 of the thesis by assessing how different factors influence the size of the footprint.

8.2 POTENTIAL DETERMINANTS OF ECOLOGICAL FOOTPRINTS

National ecological footprints are driven by a vast array of parameters as discussed in Chapter 6. They represent the consumption and waste assimilation for a given population, and as such vary significantly between differing nation states. A large range of variables was therefore considered to be potential determinants of the ecological footprint.

The footprint is primarily a consumption based indicator, measuring how much of Nature's resources humanity requires in a year. Hence factors affecting the footprint were formulated around this consumptive theory. For example, populations need feeding, and as such the yield of crops is important. Parameters that may influence the growth of such crops, like temperature and soil fertility were also considered valid. Technology was assessed as it may be able to improve efficiencies, reduce waste and have a serious effect in reducing the footprint.

Waste is also accounted for within the footprint methodology. One of the dangerous waste products produced by humanity is carbon dioxide; this is included within footprint calculations. Thus the amount of anthropogenic carbon released into the atmosphere was considered to be highly influential upon the footprint.

Considering the breakdown of the footprint into its individual components – cropland, grazing land, forest, built-up land, fishing grounds and land used for carbon sequestration – national *per capita* ecological footprints were initially postulated to be a function of 13 variables:

- Economic well-being
- Population density
- Energy intensity
- Carbon emissions ratio
- Temperature ratio
- Precipitation ratio
- Yield ratio
- Technology ratio
- Soil fertility
- Terrain
- Latitude
- Fertiliser ratio
- Irrigation ratio

Each of these factors was judged to have an influence upon the ecological footprint.

8.2.1 Economic Well-being

Economic well-being was measured in terms of Gross National Income (GNI) on a 'purchasing power parity' basis from the World Bank's *World Development Indicators 2005* (World Bank, 2005). GNI was selected as the economic indicator since it represents the total value produced within a country as well as flows of income from abroad. This is in line with the footprinting methodology of 'trade correcting' for imports and exports to ensure that results are based upon consumption rather than production within a given country. Purchasing power parity (PPP) is a useful conversion factor, which accounts for differences in price of goods and services, providing a better overall measure of the real value of output produced by an economy compared to other economies. The 'Big Mac Index' is the measure of PPP made popular by The Economist in 1986 (see for example The Economist (2010)). It follows the theory that one international dollar should purchase the same amount of good in any country, in this case a McDonald's Big Mac. PPP GNI was therefore adopted to represent economic well-being in this study. It is measured in current international dollars which have the same purchasing power as a dollar spent on GNI in the U.S. economy.

The use of this indicator is limited since GNI does not include any economic activities such as housework or childcare. Nor does it allow for depletion in natural capital and resources. It simply represents financial flows, all those goods and services that are part of a formal economy. The developing world is therefore less well represented by this type of measure, where many women do not work and family care is considered

important. However, this limitation crosses all nation states and is constant in its ability to show economic development. It is an internationally accepted indicator and was appropriate for the study undertaken here.

8.2.2 Population Density

Since the footprint is a spatial indicator, population density was adopted – this represents the number of people per hectare for a given country. Population size was measured in millions sourced from the WWF's *Living Planet Report* (WWF International, 2006) and land area in km² sourced from the *World Databank* (World Bank, 2007).

8.2.3 Energy Intensity

Energy intensity is a measure of the energy efficiency of national economies. It represents the joules of energy generated per dollar for a particular nation state. This is based upon the amount of energy consumed by a population within a nation state.

This indicator should reduce as energy saving technologies continue to be developed and efficiency levels improve. Thus the ecological footprint was expected to be dependent upon this intensity; energy intensities may decrease as efficiencies and technology progress, creating a shrinking footprint.

Primary energy use was taken from World Bank's *World Development Indicators 2005* (World Bank, 2005), measured in EJ. Primary energy represents any indigenous production, including imports and excluding exports. This energy was converted to an intensity by dividing through by per capita national income.

8.2.4 Carbon Ratio

The carbon ratio is the amount of carbon released per joule of energy consumed. The footprints of many nations are dominated by the carbon segment, or energy land footprint, which represents their carbon emissions. However, the emissions given off per unit of energy should show how efficiently a nation converts energy into a useable format. Carbon dioxide (CO₂) emissions, in Mt per person, were adopted from the Carbon Dioxide Information Analysis Center (Marland *et al.*, 2007). These were converted to a carbon ratio by using the energy intensity described above.

8.2.5 Climatic Factors

Average national temperatures, measured in °C, were taken from the Tyndall Centre for Climate Change Research (Mitchell, 2003). For analysis purposes within this study, a non-dimensional Temperature Ratio (TR) was formed. This was the result of dividing each nation by the average 'World' temperature, which itself was a result of aggregating the area weighted mean temperature of each nation. Average national precipitation, measured in mm, was established from the Tyndall Centre for Climate Change Research (Mitchell, 2003). A Precipitation Ratio (PR) was formed by the same method as the Temperature Ratio.

Latitude was also considered to affect the footprint. For example, the position of countries close to the poles would affect energy use, crop yields and consumption levels alike. This was measured in degrees from the equator (CIA, 2007). The approximate geographic centre of each country was assumed, based on the locations provided by the Geographic Names Server (GNS, 2010).

Mean national values for both temperature and precipitation were analysed. Clearly there are inaccuracies in taking averages for larger countries with considerable internal geographic variations. However, accurate datasets were difficult to discriminate between climatic variations and crop yields within large (sub-continental) nations.

8.2.6 Technological Improvements

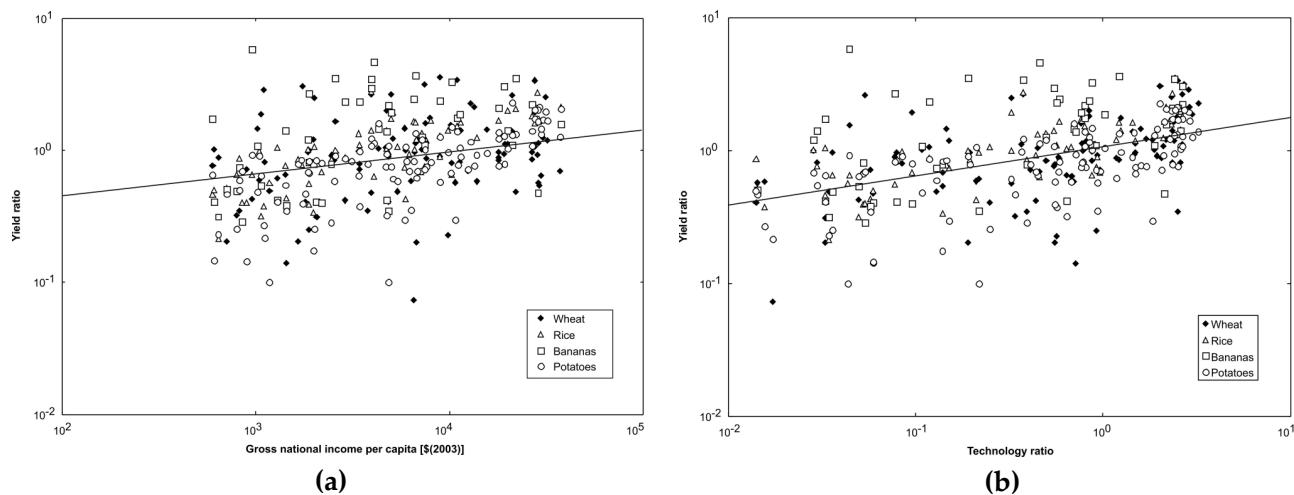
Technological improvements are plentiful and extremely varied. A common development across countries throughout the world was selected. As such, the level of technological advancement was measured by the number of fixed lines and mobile telephones per thousand in a nation (World Bank, 2007). The technology ratio was established from the number of phone subscribers per thousand citizens in each country and dividing by the average world subscribers per thousand citizens. An alternative high-technology ratio was also considered, using the number of internet subscribers per thousand people; however this returned very similar final results and was therefore not necessary as an additional or alternative parameter particularly as data availability for some nation states was poor.

8.2.7 Crop Yield

8.2.7.1 *Choice of crop*

Crop yield had to be measured using a standardised crop type. Not all countries have a common crop and the yields from region to region vary. However, wheat was chosen as a marker crop since it is the most common crop in the world, grown in 115 of the 145 nations analysed in the WWF *Living Planet Report 2006* (WWF International, 2006) and is harvested in all continents excepting Antarctica. However, in many countries it is not the dominant crop. Such limitations were regarded throughout this analysis.

In order to consider such a vast selection of countries it was necessary to select a proxy for all crops. Alternative crops that are also commonly grown around the globe were assessed – rice, potatoes and bananas – these are predominant in cultivation throughout the world (FAOSTAT, 2009b). These showed the same trends as wheat (see for example Figure 8-1) with a similar scatter with respect to both economic welfare and technology ratio.



**Figure 8-1: Comparison of Yields for Alternative Crop Types with
(a) National Income (b) Technology Ratio (2003)**

The disadvantage with these other crop types was that they are not grown in as many nation states as wheat (Table 8-1), and therefore do not represent the full scope of nation states that were being assessed within this study. Since the yield ratio was shown to have a dependency upon other determinants, namely upon national income, the choice of crop variety was not vitally important since this parameter was eliminated from the final correlating 'power-law' equation.

Crop	% of selected nation states cultivating crop type
Rice	61
Potatoes	98
Bananas	48

Table 8-1: Percentage of alternative crops grown in nation states

Wheat yield is given by the Food and Agriculture Organisation in hectograms per hectare (a hectogram is one hundred grams) (FAOSTAT, 2007). Although some nations have higher absolute yields than others, the wheat harvested on a given area of land provided a useful measure of crop productivity and yield. Wheat, the most widespread crop in the World, was therefore used as proxy for all crops. This was based on the amount of a representative crop grown per unit of cropland, or yield. The yield data was non-dimensionalised to form a yield ratio using the method applied to temperature and precipitation.

8.2.7.2 Fertiliser and Irrigation

Fertiliser and irrigation have both been identified as ways of improving crop yield. Fertiliser ratio was calculated based upon the consumption of total fertilisers (FAOSTAT, 2009a); that is the quantity of fertiliser in metric tons of plant nutrient consumed in agriculture by a country. The ratio was the consumption per country

divided by the total world average quantity of fertiliser. Irrigation ratio used the agricultural area irrigated which included arable land, land under permanent crops and land under permanent meadows and pastures (FAOSTAT, 2008). It was determined using the same methodology as the fertiliser ratio.

8.2.8 Soil Fertility

It was difficult to define soil fertility for different nation states from around the world as some areas suffer from deficiencies in certain nutrients, whilst others are nutrient rich. Soils with a low cation exchange capacity (CEC) have a low inherent fertility, as well as a low capacity to retain nutrients added as fertiliser (Bot *et al.*, 2000). This was considered a suitable indicator to identify a standard level of soil fertility globally. Cation exchange is a phenomenon that occurs in soils. It represents a mechanism to temporarily hold cations in the soil, allowing plants to obtain sufficient quantities of the essential nutrients to grow. Without cation exchange, the nutrients would be leached into the soil and lost. Soils with low CEC have topsoils with a low organic matter content and low clay content. They therefore have inherently low fertility and a poor capacity to retain nutrients added as fertiliser (Bot *et al.*, 2000).

An assessment of the impact of CEC was undertaken. Data for soil fertility was taken from the FAO AGL (2003) based upon levels of low cation exchange capacity (CEC), measured in cmol_c/kg (this is centimoles of charge per kilogram of soil).

8.2.9 Terrain

Terrain was difficult to measure, as there are many different types. The assessment of terrain was made in terms of 'steeplands'. The United Nations (1999) in preparing its landmark document associated with its Agenda 21 programme implied that mountainous regions are at high altitudes and have steep slopes. However, it is not necessarily the case that only steep slopes at high altitudes give rise to problems associated with land slip and soil erosion. Lowland slopes are also vulnerable to these effects; for instance in the East African Rift Valley. Thus, the FAO data for steeplands was utilised here (FAO AGL, 2003). They suggest that 'steeplands' are the class of terrain that has dominant slopes of greater than 30% incline. Once again a ratio was applied for each nation state against the world average steeplands.

8.2.10 Data

A large selection of data was chosen to represent the 13 variables in the 'power-law' equation. Where possible the same sources were utilised to ensure continuity between the variables. The same data sources were also adopted, when appropriate, as those utilised by Hammond (2006a) in order to ensure comparability. The statistical dataset contained 109 countries in total, for the year 2003, from which the situation in the G8 + 5 nations is highlighted.

8.3 INITIAL CORRELATING EQUATION

A selection of 13 different variables was identified as having an impact upon *per capita* national ecological footprints (*ef*). This can be expressed in the form of an analytical equation:

$$ef = f \{ (GNI) (PD) (EI) (CR) (Temp R) (PR) (YR) (Tech R) (SF) (Terr) (L) (FR) (IR) \} \quad 8-1$$

These factors are summarised in Table 8-2.

Determinant	Abbr.	Unit
National Ecological footprint	(<i>ef</i>)	[gha per capita]
Economic Wealth	(GNI)	[per capita \$]
Population Density	(PD)	[people per hectare]
Energy Intensity	(EI)	[MJ/\$]
Carbon Emissions Ratio	(CR)	[μg C/J]
Temperature Ratio	(Temp R)	[-]
Precipitation Ratio	(PR)	[-]
Yield Ratio	(YR)	[-]
Technology Ratio	(Tech R)	[-]
Soil Fertility Ratio	(SF)	[-]
Terrain Ratio	(Terr)	[-]
Latitude	(L)	[°]
Fertiliser Ratio	(FR)	[-]
Irrigation Ratio	(IR)	[-]

Table 8-2: Parameters considered within the correlating ‘power-law’ equation

In order to evaluate the importance of each individual parameter within this expression, it was more useful to represent *per capita* ecological footprints (*ef*) as a function of various independent variables in the form of a ‘power-law’ correlating equation (see Chapter 7). Therefore an expression was formulated to indicate the relative significance of these factors:

$$ef = \text{constant} \{ (GNI)^a (PD)^b (EI)^c (CR)^d (Temp R)^e (PR)^f (YR)^g (Tech R)^h (SF)^i (Terr)^j (L)^k (FR)^l (IR)^m \} \quad 8-2$$

Here each of the determinants was raised to a power (a-m), (see Chapter 7 for details). The powers were analysed and substituted by a numeric value. These values represent the strength with which the variables are related to the footprint; the larger the power, the more dominant the parameter. Indeed scaling of this type is a common approach used in engineering and the thermal sciences (Duncan, 1953; Kline, 1986). Such expressions reflect the relationship between size and rank in a sample, represented by

an equation in which the independent variables are raised to powers (Hammond, 2006). This has been shown to be a robust method traditionally employed to correlate experimental data, for example, heat transfer phenomenon that are often underpinned by rate equations.

The 'constant' in the 'power-law' correlation effectively includes a unit converter that ensures that the equation satisfies the so-called 'principle of homogeneity of dimensions' (see, for instance, Hammond, 2006). In order to determine the empirical coefficients (both the constant and the exponents) in this correlation equation, a range of international statistics were utilised for the year 2003 (as highlighted in section 8.2). Thus the national ecological footprints computed for the *Living Planet Report 2006* (WWF International, 2006) as well as other parameters from international datasets, were employed to identify the main determinants of humanity's environmental impact.

8.3.1 Excessive variables

The initial correlating 'power-law' equation was expansive. The adoption of every variable has been discussed, and each was justified within the remit of the research. However, it was not expected that the expression would remain so detailed, following careful analysis of each determinant and given that there must be no interdependencies as stated in Chapter 7. Indeed, it was not appropriate to have so many parameters, given the inaccuracy within international data sets for several of the factors.

Correlation of this sort requires the variables to be independent of each other, and that the *per capita* ecological footprint should ideally be strongly dependent on specific factors. It was anticipated that some of the variables would be dependent on each other; that is cross-correlated. Analytical techniques were applied to ensure that cross-correlation was identified and that the final determinants in the 'power-law' equation were completely independent and strongly influential upon the footprint.

8.4 ANALYSING THE CORRELATING 'POWER-LAW' EQUATION

Analysis commenced by verifying which of the determinants had the best correlation with the *per capita* footprint and was the most dominant. Plots were drawn to establish such relationships and the strongest dependencies were identified. Many variables showed very little affect upon the footprint, and others were proven to be dependent upon more important determinants, thus having to be excluded from the final 'power-law' equation.

Each individual parameter was scrutinised, and it was concluded that only two determinants could ultimately be included within final expression, these being economic welfare and population density.

8.4.1 Determining the dominating determinants

Few of the 13 determinants selected to be analysed had strong correlations with the *per capita* national ecological footprint. Economic well-being, technology ratio and yield ratio were the only three parameters that showed any relationships of note. It was thought that when the footprint was combined with the most dominant parameter, other factors may show better correlations.

The determinant with the strongest power-law dependency had to be identified. It was vital that all the determinants were completely independent. Any cross-correlation or co-dependency would result in double counting in the final 'power-law' expression. Thus the three most well correlated factors were carefully scrutinised.

8.4.1.1 Yield ratio co-dependencies

It was postulated that there would be a relationship between yield ratio and the various climatic and geographic factors. For example, crops were anticipated to be more plentiful given appropriate temperatures, precipitation levels and fertile land. Surprisingly there was very little correlation between yield ratio and the following factors: precipitation ratio, temperature ratio, irrigation, terrain and soil fertility (see, for example, Figure 8-2).

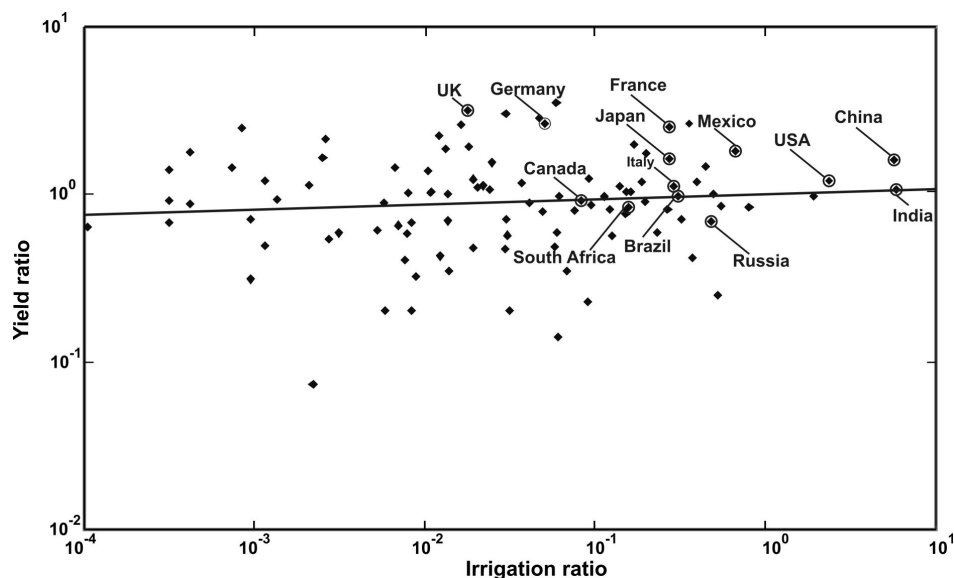


Figure 8-2: Poor relationship between yield ratio and irrigation ratio (2003)
(G8+5 nations identified)

Irrigation is not adopted everywhere throughout the world; some countries can't afford irrigation systems and others that have a wetter climate, may not require irrigation at all. For example, the UK has a high yield ratio but maintains a low irrigation ratio (see Figure 8-2), since it has weather conditions that do not necessitate the use of irrigation. The USA has a varied climate, and as such some regions require crops to be watered

through irrigation. Such wealthy countries will have the resources to integrate irrigation into farming techniques and also use technology to allow for automated watering systems. Poorer countries, with vast expanses of arid land, do not have easy access to fresh water, let alone have the ability to implement irrigation systems. This can perhaps explain why yield ratio is driven by wealth rather than any climatic parameter. Precipitation was also shown to have little effect on yield values. Thus the quantity of water, be it from natural rainfall or manually implemented irrigation, has little impact on crop production. What is most telling is the comparison of precipitation and irrigation ratios (Figure 8-3). It might have been expected to see a relationship with these two factors, such that nation states with less rainfall would have a higher level of irrigation; this is not the case. The data is completely scattered, showing no overall trend. This indicates that wealth and technological development are the major factors for the use of irrigation, as discussed below.

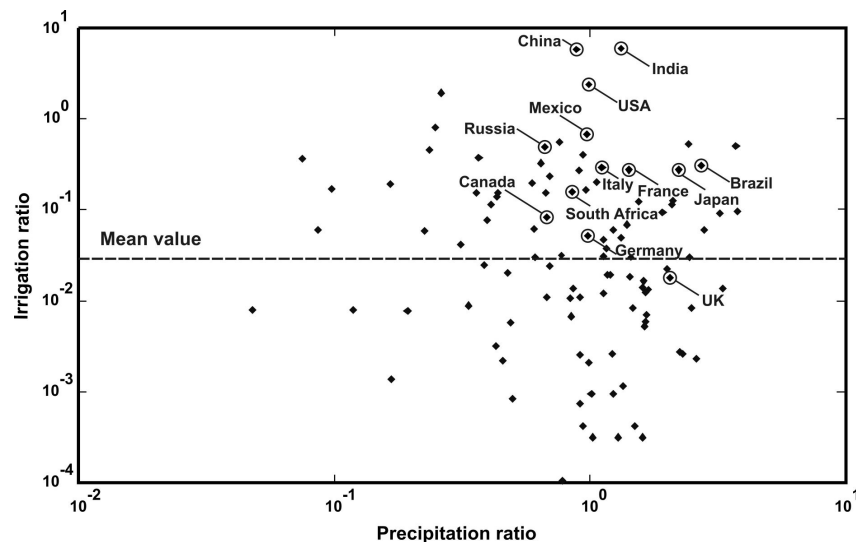


Figure 8-3: Poor relationship between precipitation and irrigation (2003)
(G8+5 nations identified)

It was proven that precipitation, temperature, terrain, soil fertility, and indeed latitude make little difference to the overall yield ratio and consequently to *per capita* national ecological footprints, as shown for example in Figure 8-2, and had to be eliminated from the final correlating equation (see also section 8.4.2). The insignificance of these variables can be explained when contrasting mass producing farms and smaller sized farms. Many small scale farmers in different countries adapt their farming techniques to their geographic location, terrain and climate to maximise their crop productivity. For example, in the UK farmers have been using crop rotation and leaving fields to fallow since medieval times (Hall, 1998). Many small scale farmers still follow these practises to ensure nutrients are restored to the soil and crop yield remains plentiful year to year, whilst mass produced crop farmers tend not to follow such traditional methods but rely upon advanced technologies to increase crop yields. It is the

development in technologies and growth in economic welfare that allows large improvements in crop harvest to be manifest and as such affluence is a far more dominating factor upon yield productivity than any climatic or geographic variable. Therefore those countries in the economic position to facilitate the use of fertilisers and advanced machinery and techniques, have higher crop yields. This was reflected in the results shown, for example, in Figure 8-4, where the yield ratio is driven by wealth, fertiliser use and technological advancement.

It was concluded that the only factors that showed a strong link to the yield ratio were technology ratio, fertiliser ratio and economic wealth. This result was intuitive; there are greater gains in yield given a high availability of wealth to enable the use of fertilisers and advanced technologies. Figure 8-4 indicates this trend, with many of the European countries clustered at the high end of national income and with superior yield ratios. In contrast the developing countries are more scattered, with lower GNI and yield values.

The firm relationship between yield and technology, income and fertiliser has been established (see for example, Figure 8-4). However, these three factors were all themselves strongly linked to economic prosperity; characterised by per capita GNI. The overriding factor influencing yield was therefore economic well-being; which itself drives technological progress (see section 8.4.1.2 and Figure 8-5). Due to this cross-correlation, the yield ratio had to be removed from the final correlating equation.

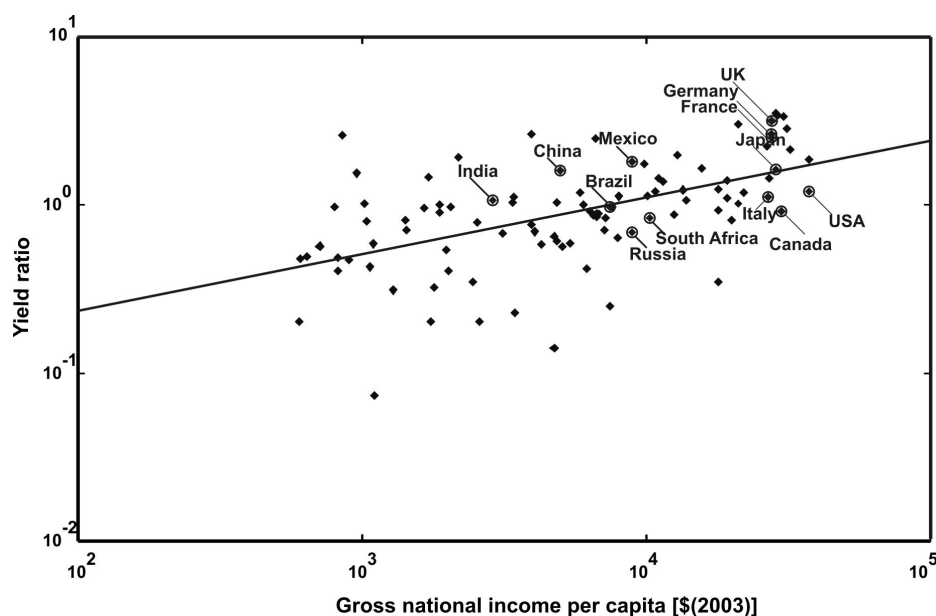


Figure 8-4: Co-dependence of yield ratio upon economic wealth (2003)

(G8+5 nations identified)

8.4.1.2 Technology ratio co-dependencies

The technology ratio was identified as being strongly related to the yield ratio (section 8.4.1.1); advances in technology enable the growth of crops to become more efficient and more plentiful. For example, Syngenta, one of the world leaders in agribusiness marketing seeds and pesticides, is developing crop protection and seed technology to meet the increasing demand for food, feed and fuel that will result from the world's growing population and subsequent demands (Syngenta, 2010). The aim of some such companies is to make technology globally available and help farmers in areas in the greatest need, such as in emerging markets.

Economic wealth and technology are interdependent (see Figure 8-5). Richer nations can afford to invest in technological development and implement such advances rapidly. Countries whose economies are not booming, are struggling to provide basic requirements such as housing, food and sanitation and cannot afford to cultivate their limited technological resources. Figure 8-5 shows that the developed countries, highlighted by the G8, are clustered together (with the exception of Russia), where both national income and technology ratio are high. The emerging economies of nations such as China and South Africa are further down the plot, but in time may well soon catch up with the prosperous countries as they rapidly advance towards industrialisation.

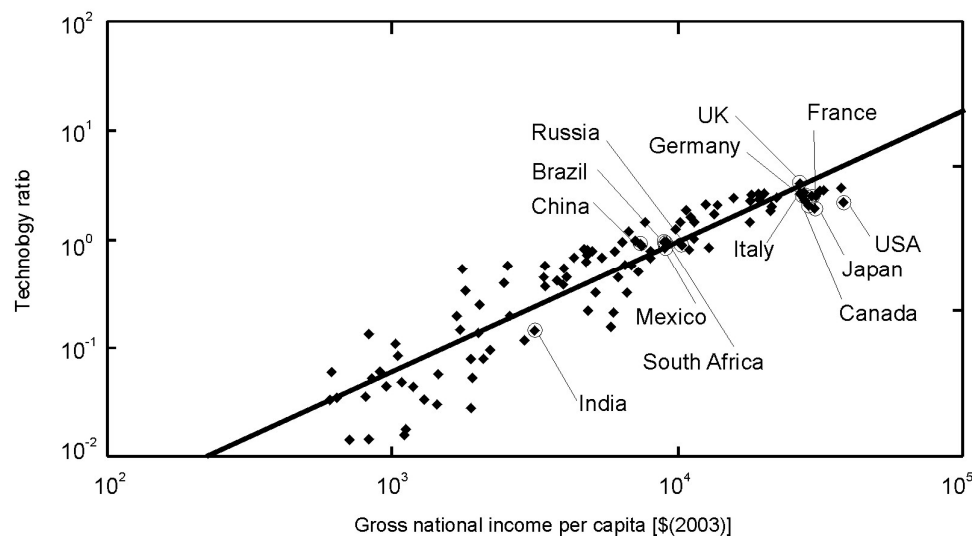


Figure 8-5: The dependence of the technology ratio for nation states of the world (2003)

(G8+5 nations identified)

The interdependency between affluence and technology necessitated the latter to be removed from the final 'power-law' equation, to prevent double counting from occurring.

8.4.1.3 Economic welfare co-dependencies

Economic wealth was shown to be the most influential factor over the *per capita* national ecological footprint, with its exponent $\sim 2/3$ (Figure 8-6).

The ecological footprint is fundamentally driven by the consumption of mankind (Ferguson, 2002). It measures humanity's impacts upon the Earth in terms of yearly expenditure regardless of the availability of resources or over-indulgence of wealthy nation states. Thus it follows that those populations with a thriving economy would have a larger ecological footprint.

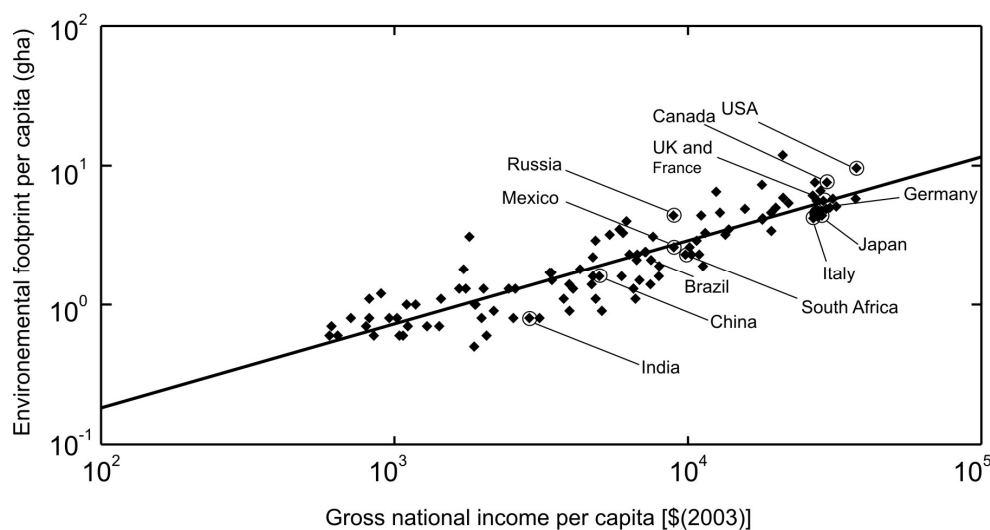


Figure 8-6: Economic wealth dominates national ecological footprints (2003)

(G8+5 nations identified)

As discussed above, economic welfare drives forward the other two most dominant determinants: yield ratio and technology ratio. Many of the other variables are co-dependent upon economic welfare, and as such all had to be eliminated from the final 'power-law' equation.

It was expected that economic wealth would have an effect on energy consumption and carbon emissions. Total, absolute values were considered initially (Figure 8-7 and Figure 8-8), in order to highlight the levels of energy use and subsequent emissions associated with each nation, and not purely on a per capita basis. Energy intensity [measured in units of energy per GNI; MJ/\$(2003)] and carbon ratio [micro-grams of carbon per unit of energy; $\mu\text{g C/J}$] were then analysed to offer insight into the way in which energy and carbon are utilised with respect to per capita wealth. The rapidly developing countries, such as China and India, are among the largest consumers of total primary energy (Figure 8-7) and, correspondingly, total CO₂ emissions in the world (Figure 8-8). However, India and China are below the international mean in terms of

energy intensity (see Figure 8-10, pp.112); although they have above average carbon ratios (see Figure 8-11, pp.112).

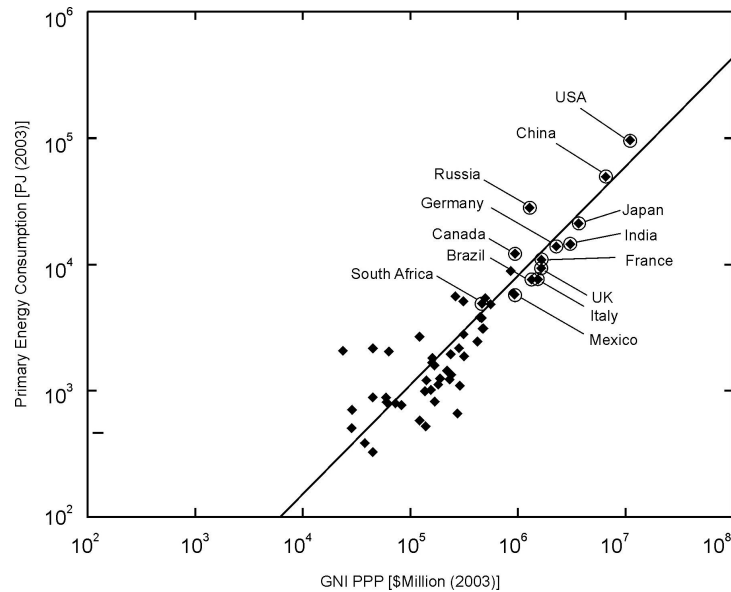


Figure 8-7: The primary energy consumption of nation states from around the world (2003)

(G8+5 nations identified)

It was shown that primary energy consumption (for 2003 data) and associated carbon emissions were strongly related to national income (Figure 8-7 and Figure 8-8). It was therefore necessary for these parameters to be eliminated from the 'power-law' equation as they displayed a close dependence upon national economic welfare. To include them in the correlation would amount to double accounting for the effects of economic well-being.

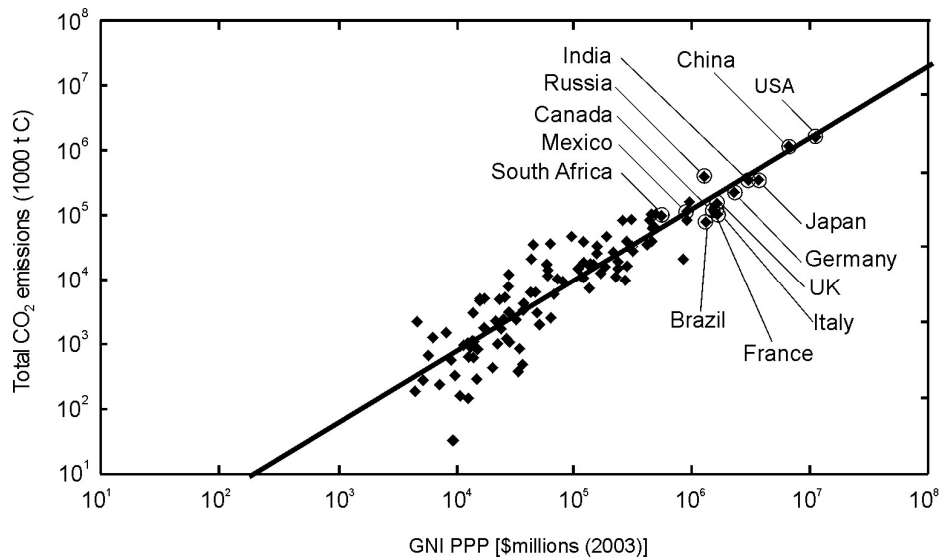


Figure 8-8: Total annual carbon dioxide emissions for nations around the world (2003)

(G8+5 nations identified)

8.4.2 Determinants with no influence

Most of the wide range of additional parameters tested was found not to significantly affect *per capita* national ecological footprints: the temperature ratio, precipitation ratio, terrain, and latitude. These plots showed very little correlation, with insignificant indices, such that:

$$e \sim f \sim j \sim k \sim 0$$

As such, these parameters were removed from the final correlating expression.

8.4.3 Population Density

Population density had previously been found by Hammond (2006a) to have a weak relationship with the national *per capita* ecological footprint, the exponent 'b' having a value of -1/4. It was expected that population density would indeed have an effect upon the footprint.

Areas that are more heavily populated than others are less likely to be self-sustaining and have a greater dependence upon external regions. Population is considered by many to be a serious problem in terms of sustainability both locally and globally. The resource demands associated with a growing population are well beyond those that can be met by Nature's regenerative capacity per year. The Optimum Population Trust is campaigning to reduce and stabilise the global population in order to achieve environmental sustainable levels of worldwide inhabitants (Optimum Population Trust, 2009). It considers that this is necessary to guarantee environmental survival and prevent serious ecological consequences. They promote a 'stop at two' policy to reduce the impact of family size on the planet (Optimum Population Trust, 2007).

Population density showed no co-dependence on any other parameters, and as such was the only remaining parameter to be assessed within the correlating 'power-law' equation. Since economic wealth was proven to be the most strongly correlated determinant with the footprint, these two factors were combined, in order that population density could be assessed against them both (Figure 8-9). This resulted in a dependency of population density that was significantly weaker than that found earlier by Hammond (2006a): the exponent 'b' was found to be -1/10 as opposed to -1/4. This can be explained since Hammond's study was based upon 1999-2000 data, whilst the present study utilised more recent 2003 data, and so some differences were expected.

8.5 DEVELOPMENT OF THE FINAL EXPRESSION

'Power-law' correlation provides a means for assessing the significance of each independent variable in respect to national ecological footprints. Each parameter was initially plotted against the *per capita* ecological footprints in order to determine the strongest power-law dependency. The remaining variables were then plotted against

this combination in order to find additional dependencies. Many of the parameters were eliminated from the ‘power-law’ correlating equation in this way due to their cross-correlation with the more influential determinants, usually GNI, or because they have negligible influence on ef . When the values for all the exponents were substituted into the original ef expression, a reduced-form ‘power-law’ correlation was obtained:

$$ef = 0.0055 \times \text{GNI}^{2/3} \times \text{PD}^{-1/10} \quad 8-3$$

This equation demonstrates that the ecological footprint is heavily dependent upon national income and weakly so on population density (Figure 8-9) in a similar manner to that previously found by Hammond (2006a). However, the dependency of population density is significantly weaker than that found earlier: the exponent b was found to be $-1/10$ as opposed to $-1/4$. The statistical trend line for the present data displayed a very weak negative correlation; although the R-squared value (which was close to zero) indicated that the data fit with the relationship was poor. This result was verified through multi-linear regression.

The ‘power-law’ equation had originally been found to be equation 8-4 by Cranston *et al.* (2010). However, upon very close scrutiny of the resultant plots, it was determined that the constant should be slightly smaller to reach the appropriate correlating line through the selection of different nation states. This proved to make very little difference to any of the subsequent results or discussions surrounding the ‘power-law’ equation, but is purely a mathematical error that needed to be resolved.

$$ef = 0.0093 \times \text{GNI}^{2/3} \times \text{PD}^{-1/10} \quad 8-4$$

8.5.1 Uncertainty in the Data

The scatter of data amounts to an uncertainty interval in ef equivalent to a standard deviation of some 100% (see, for example, Figure 8-9). This would appear large to a physical scientist, but is in keeping with the scatter inherent in many datasets related to human affairs found in the domain of social scientists (Hammond, 2006a). There are various factors that cause the broad spread of correlated data, such as the uncertainty associated with international datasets and the relatively poor quality data for some developing countries. Statistical information can be scarce and of varying accuracy, particularly in the developing world, where energy use, for example, is often underestimated through the high use of non-commercial fuels, such as wood and peat. In this type of analysis when looking at so many different nation states, with various parameters, it is not possible to maintain the accuracy usually expected of scientists and engineers.

8.5.2 Frugal or profligate use of Nature's resources

The inclusion of population density in the 'power-law' correlation (see Figure 8-9) allowed for an assessment to be made of whether countries with a similar combination of income and population density have comparably scaled ecological footprints. Their position, in relation to the power-law data correlation, implies that given countries have footprints typical (that is, close to the 'mean' value) of nation states with a similar combination of income and population density. The relative position therefore indicates whether specific nations are profligate or frugal in terms of the use of natural capital. Those located above the 'power-law' correlation curve are wasteful, whilst those below it are more careful in terms of their resource use (Figure 8-9). The European G8 countries and Japan were clustered together on the curve (see Figure 8-9), highlighting their close relationship to the average use of Nature's resources. The Russian Federation and the USA were seen to have *per capita* ecological footprints just above the correlation equation, proving that they are more wasteful of natural capital, and could make improvements in order to tally with the correlating curve. The emerging economies, such as China, India and South Africa were evidently more sparing in their use of natural capital on this basis.

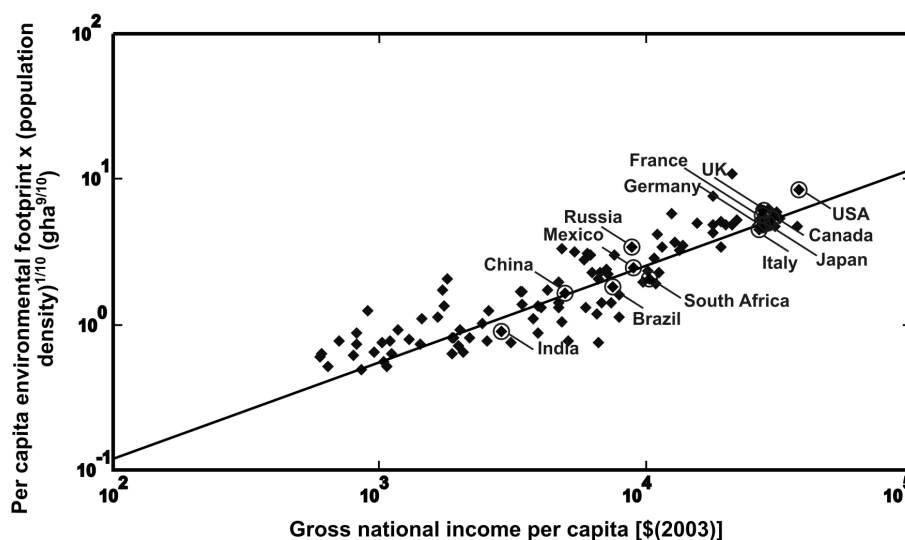


Figure 8-9: The dependence of *per capita* national ecological footprints on per capita national income and population density (2003)
(G8+5 nations identified)

Nation states that are placed above and below the curve are distributed across the spectrum of socio-economic groups; national consumption patterns of biophysical resources do not appear to be related to wealth or poverty per se.

The correlating equation and resultant curve (Figure 8-9) indicate the position where nation states have a characteristic combination of ecological footprint, population density and economic wealth for the year 2003. This equation will change from year to

year, as countries' economies begin to emerge, populations grow and states begin to strive for a sustainable world. Although it has been shown that some nations are profligate and others frugal in terms of their resource use, this is only in comparison to the typical values. Making reductions to move a nation to below the curve would be an improvement, and that nation would indeed be shown to be thrifty in its spending of Nature's natural capital compared to other nation states. However, the world is already in overshoot, and it is not enough for countries to achieve these average values. Indeed, in 2003, the average *per capita* footprint was 2.2 gha, whilst the biocapacity available to each person on the Earth was only 1.8 gha (WWF International, 2006). This results in an ecological deficit of -0.4 gha per person. As such, nation states must take large steps, with smaller footprints, in order to diminish the global ecological debt that is continuing to grow.

8.6 HUMAN APPROPRIATION OF NATURAL CAPITAL

The national ecological footprint can be used to assess many aspects of resource and energy use. The G8+5 nation states have been highlighted throughout the analysis of the correlating 'power-law' equation, and illustrated the differences between the industrialised and developing world. Developed nations (including the G8 countries) tend to be more services orientated, and are therefore less energy intensive than the developing countries, where heavy industry is sometimes a dominant force in the economy. The exception was found to be the Russian Federation, which had a notably high value for its energy intensity (Figure 8-10); implying a wasteful use of energy. This may stem from the relative inefficiency of heavy industries under the pre-1990 Communist regime that was a result of a economic strategy of rapid industrialisation (Hammond, 2006a). The USA has an energy intensity close to the international mean value (see Figure 8-10). Other G8 industrialised nations, including those from the European Union [France, Germany, Italy, and the UK], and Japan have energy intensities significantly below this mean in 2003. Here primary energy is restricted to commercially traded sources only. Non-commercial fuels, such as animal wastes, peat and wood, play an important role in many developing countries, but they are poorly recorded in national energy statistics. Goldemberg (1996) estimates that such non-commercial sources contribute around 23% of the total energy consumed in the majority South; the African, Asian and Latin American regions of the world. Fossil fuel consumption typically accounts for between some 33% and 60% of national ecological footprints for low-income and high-income countries respectively (Hammond, 2006a). Emerging countries like China and South Africa have energy intensities also close to the international mean value (see again Figure 8-10). In contrast, Brazil, India and Mexico have similar values to the EU G8 nations.

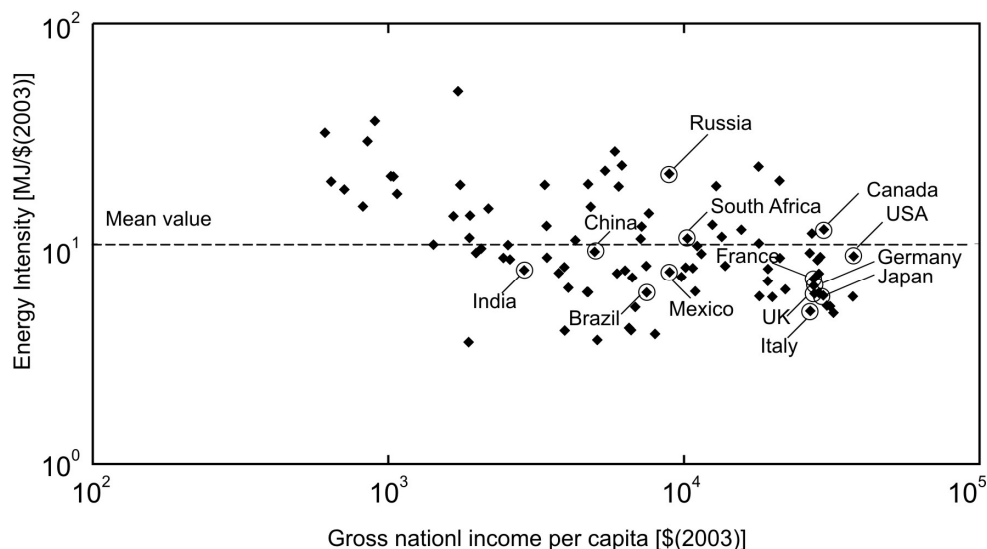


Figure 8-10: The energy intensities of nation states around the world (2003)

(G8+5 nations identified)

Overall, energy intensities can be seen to decrease with national income (Figure 8-10); a trend that would be required to continue in order to steer nations towards sustainable development. This implies the use of better efficiencies in the more wealthy nation states; such countries are more dependent upon services and are thus less energy intense. Despite this reduction in energy intensity with respect to increasing per capita wealth, the carbon ratio did not differ greatly (Figure 8-11). The developed, rich world has better energy efficiency, due to higher levels of technology and wealth, but it doesn't follow that the release of carbon per joule is lower.

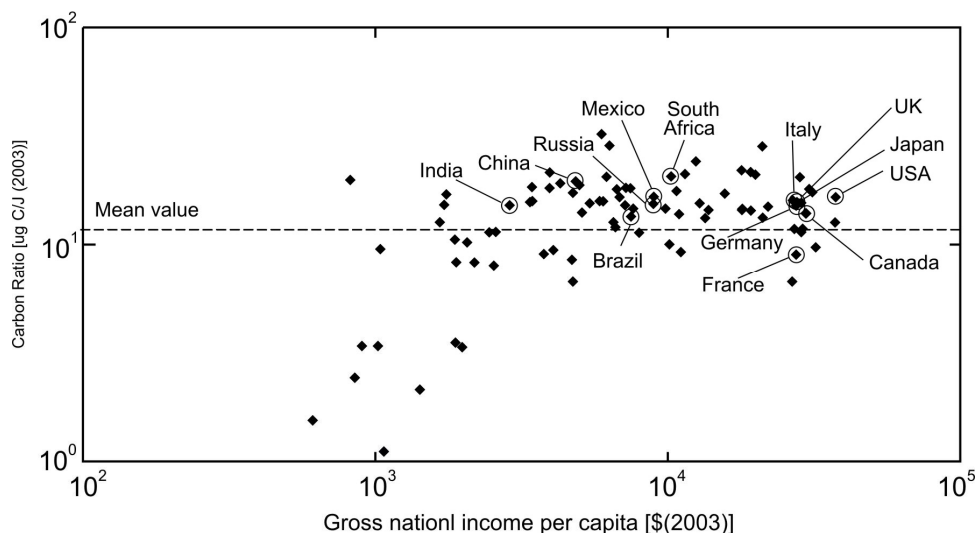


Figure 8-11: The carbon ratios associated with individual countries from across the world (2003)

(G8+5 nations identified)

The carbon ratio contrasts to the energy intensity in that it generally reflects the extent to which nations are dependent on particular types of energy resource – principally coal, oil, natural gas and nuclear power. The latter, together with ‘renewable’ energy technologies, provide a near-zero carbon resource. National carbon ratios (see Figure 8-11) are even more closely clustered around the global mean value than are the energy intensities, with just a few low-value outliers – such as developing countries (not part of the G8 + 5 grouping) that principally draw carbon-free hydropower. China and India, along with other developing countries, are more dependent on ‘dirty’ fuels, like wood and coal resulting in their relatively high carbon ratios. Developed nations should clearly be more carbon efficient, because of their advanced technology. But the actual amount of carbon released per Joule does not vary greatly with per capita national income (see again Figure 8-11). Industrialised G8 countries tend to use oil, natural gas and nuclear power. France’s relatively low carbon ratio can be attributed to the many nuclear power stations that supply the country with the bulk of its electricity.

There is clearly a stark contrast between the industrialised North and the developing South; not only in terms of their resource use, but also looking at carbon emissions, technological advancement and economic wealth. The final correlating ‘power-law’ equation is used to assess the position of each nation state as they move along the sustainability pathway towards a more balanced world.

8.7 ECOLOGICAL DEBT

Ecological debt indicates those countries that are using natural resources beyond their capacity (see Chapter 4). It appears that the human appropriation of natural capital exceeded that available on the planet in 1987 (Global Footprint Network, 2006a; New Scientist, 2006). There is clearly a need over the long-term to bring the Earth’s ecological footprint back into balance with its biocapacity.

Nation states import resources from beyond their borders and likewise export materials, goods and services; however, they are rarely in trade balance. In addition, pollutant emissions and wastes can have an impact on a local, regional, and international scale. The environmental consequences of such cross-border flows can be presented in terms of a country’s ecological debt with other nations; if the ecological footprint is analogous to individual ‘spending’, then the biocapacity would reflect their ‘credit limit’. It has been found that, in general, this ecological debt is owed by the industrialised countries of the North to the developing nations of the populous South (Simms, 2005). A closely related parameter is the overshoot ratio (OR) (Hammond, 2006a) defined as:

$$\text{Overshoot ratio} = \text{national ecological footprint/biocapacity} \quad 8-5$$

Those countries that owe an ecological debt to other nations or regions will exhibit an overshoot ratio greater than unity ($OR = 1$), and vice versa.

Industrialised countries of the G8 have overshoot ratios significantly higher than one (Figure 8-12). The European Union (EU-27) has a mean value of OR = 2.18 [based on 2003 data (WWF International, 2006)] with the EU G8 members having values of France 1.87, Germany 2.65, Italy 4.20, and UK 3.50 (Cranston *et al.*, 2010). They all owe an ecological debt to those regions of the world (principally in the South) from which they import resources and deposit emissions and waste products. The remainder G8 nations have overshoot values of Canada 0.52, Japan 6.29, the Russian Federation 0.64, and the USA 2.04 (Cranston *et al.*, 2010) (see also the graphical presentation of 2000 data by Hammond, 2006). Only the sparsely populated countries of Canada and Russia display an ecological under-shoot and are therefore currently in ecological credit.

The five large emerging economies (Chapter 7) have overshoot ratios of Brazil 0.21, China 2.00, India 2.00, Mexico 1.53, and South Africa 1.15. In 2003 the global ecological deficit reached 0.4 gha per person; enabled by the use of fossil fuels laid down over geological timescales. Thus, although Brazil is in significant ecological credit with the rest of the world, the other emerging economies are roughly in line with the planetary mean, which overshoot its footprint by some 80% in 2003. Many poor developing countries in Africa, Asia, and Latin America are in ecological credit (see, for example, Hammond, 2006).

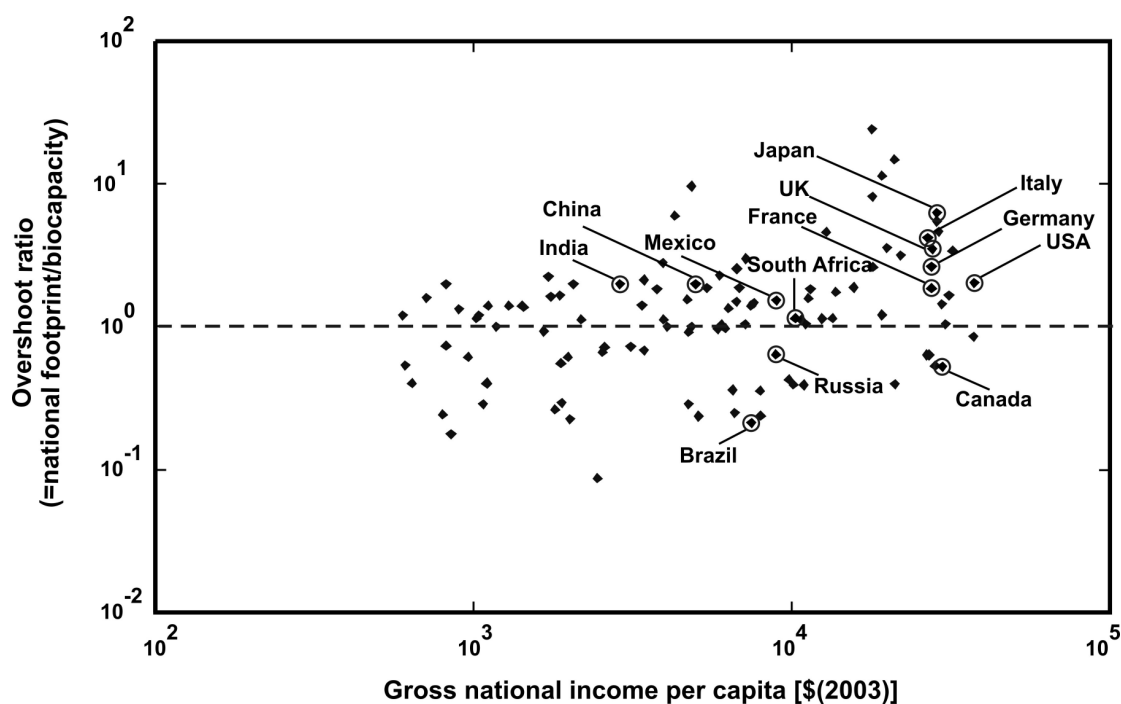


Figure 8-12: Bioclacity overshoot or undershoot of nations from around the world (2003)

(G8+5 nations identified)

A comparison with the 'Earthshare' [1.80 global hectares in 2003 (WWF International, 2006)] indicates how close humanity is to achieving 'One Planet Living' (Eaton et al., 2007). That would require a rate of consumption of natural resources equivalent to 1.8 gha per person. If the rest of the world consumed as much as is currently done in the UK, the 'standard of living' would require the resources of three planets, the USA six planets, and the United Arab Emirates (UAE) ten planets. However, it must be borne in mind that this notion of an 'Earthshare' is simply an ethical construct (Eaton et al., 2007) – a value judgement about fair national shares in environmental impacts. In practice, it is unlikely, given the disparity in global wealth and resources between the prosperous North and majority South that the different nations of the world will converge towards 'One Planet Living' during the 21st Century. This would need, for example, a major reduction in energy demand, along with a shift from a dependence on fossil fuel and uranium resources (so-called 'capital' energy sources) to renewable energy technologies (mainly solar-driven, 'income' sources) in both the industrialised and developing nations. Only then would humanity be able to secure a low carbon global economy.

Insights derived from ecological footprinting discussed here, such as the need for humanity (and, more debatably, individual countries) to live within biocapacity constraints, may aid the post-Kyoto negotiations that will ultimately need to take place amongst all the major nations and geo-economic groupings on the planet (Hammond, 2006). They may put into perspective the future GHG burden sharing arrangements between the wealthy nations of the northern hemisphere and the majority South.

8.8 SUMMARY

This chapter details the development of a correlating 'power-law' equation that demonstrates the relationship between the *per capita* ecological footprint and a host of determinants, ranging from affluence to geographic characteristics to climatic factors. The study builds upon the work of Hammond (2006a), and its original contribution is the inclusion of many more varied parameters, considering the footprint beyond the boundaries of the IPAT equation and assessing far deeper into the makeup of the fundamentals of the footprint. The footprint is in essence a consumptive indicator and this is reflected by the result that on a per capita basis the ecological footprint is driven most strongly by economic wealth. Population density is proven to be the only other factor of importance; all other determinants are insignificant or eliminated from the final equation to prevent double counting. The G8+5 nation states are highlighted to indicate individual country's consumption patterns and their profligate or frugal use of Nature's capital. This is translated into an ecological debt, demonstrating the deficit many countries find themselves in with respect to natural resources.

Aim 1 detailed in Chapter 1 is achieved within this chapter where the fundamentals of the ecological footprint are assessed in terms of key determinants that influence its growth and size. This is implemented through Objective 5, where the driving forces for

the footprint are established (also detailed in Chapter 6) and the subsequent relationships assessed using dimensional analysis and multi-linear regression.

CHAPTER 9

LOSING WEIGHT OR TREADING LIGHTLY

Understanding the Carbon Footprint

9.1 INTRODUCTION

Carbon footprints have recently received a lot of attention, not only from the media as a 'buzzword', but also from academics, policy makers and the general public alike. The carbon footprint is the largest contributor to humanity's total ecological footprint², approximately 50% (Ewing *et al.*, 2008b) (see Chapter 3). The global carbon footprint increased more than ten times from the 1961 to 2005 values, putting it as the largest demand on the biosphere from humanity (WWF International, 2008). As has been demonstrated in Chapter 8, the demand upon Nature's resources varies between countries, as does the biocapacity available within each nation state; this is considered here with particular reference to the carbon footprint, its determinants and subsequent correlating 'power-law' equation.

By considering the development of a correlating 'power-law' equation with respect to the carbon footprint, this chapter fulfils objective 9. The use of dimensional analysis and multi-linear regression is implemented to make appropriate assessment of the relationships. This work contributes to the first aim of the thesis which is to assess the effects of differing variables upon the footprint. This chapter also further develops the correlating 'power-law' for the ecological footprint, in order to compare and contrast key results with the carbon footprint.

The use and application of the carbon footprint has become popular, however, the term 'carbon footprint' is actually poorly understood and is often misused. The carbon footprint represents a proportion of the ecological footprint, an indicator that encompasses more issues than purely carbon dioxide emissions (Chapter 3). The carbon footprint is fundamentally measured in the same way as the ecological footprint. It is expressed as an area in terms of a standardised average biologically productive hectare of land (the 'global hectare'), such that various populations may be comparable with each other. This misunderstanding of the carbon footprint is developed in section 9.4 with a comparison between the standard carbon footprint as defined in this chapter and the many alternative indicators that use the same terminology. Further limitations and criticisms of the carbon footprint are discussed in Chapter 3.

² when looking at developing countries other contributions may dominate

9.2 STEPS TOWARDS DEVELOPING THE FOOTPRINT EQUATION

With the growing popularity of the carbon footprint and the recent focus upon the disparity between nation states, it was possible to establish the dominance of factors, such as varying economic wealth, upon the carbon footprint (Cranston & Hammond, 2010c). By generating a correlating equation and highlighting the G-20 nations, the need for careful environmental policy and carbon reducing strategies was demonstrated. This analysis was based upon the methodology of Cranston *et al.* (2010) and their development of the environmental correlating 'power-law' equation (Chapter 8). This *ef* equation has been updated in section 9.3 using 2005 data and is therefore comparable to the carbon footprint equation established in this chapter.

It has been shown in Chapter 8 that *per capita* national ecological footprints are strongly dependent upon per capita national income and weakly on population density; all other parameters were determined to be insignificant. The need to improve the ecological footprint of nations is currently being driven by the focus upon reductions in carbon emissions, for both the developed and developing nations. Therefore this previous analysis is developed in this chapter, with a particular focus upon the carbon footprint, culminating in a correlating 'power-law' equation relating three determinants to the carbon footprint.

9.2.1 Cracking the Carbon Correlation

A similar analysis to that presented in Chapter 8 was undertaken for the carbon footprint in light of its growing popularity as an indicator in the public domain. Four determinants were considered, all others having been eliminated (Cranston *et al.*, 2010) (see Chapter 8). Therefore the carbon footprint was postulated to be a function of economic wealth (GNI) [per capita \$], population density (PD) [population per hectare], energy intensity (EI) [MJ/\$] and carbon ratio (CR) [$\mu\text{gC/J}$]. This can be written as a correlating 'power-law' equation, as per engineering and physical sciences in equation 9-1.

$$cf = \text{constant} [(GNI)^a (PD)^b (EI)^c (CR)^d] \quad 9-1$$

Economic wealth was measured in terms of Gross National Income on a 'purchasing power parity' basis from the World Bank's *World Development Indicators* (World Bank, 2006). Population density was based upon population size in millions from the WWF (WWF International, 2008) and energy intensity took primary energy from the World Bank's *World Development Indicators 2006* (World Bank, 2006). The carbon ratio was calculated using CO₂ emissions in M tonnes from the International Energy Agency (IEA, 2008) for production and then corrected to give national consumption levels using import and export data tables from the UN Statistical Division (UNSD, 2009) as discussed in section 9.4.

To determine the significance of each of the factors a 'power-law' correlation was applied (see Chapter 7). The correlation established the dominance of each factor upon the *per capita* national carbon footprint, *cf.* Each variable was raised to a power which represents its relationship with the carbon footprint. The variables were all shown to be independent of one another such that there was no double counting or cross-correlation (Cranston & Hammond, 2010c). Multi-linear regression was applied to verify the results.

In this study a total of 107 countries were analysed for the year 2005. This does not include all the nation states of the world due to the limited availability of data, but it still offers a good range and indication of the differences within the international community of nations. The G-20 has been highlighted throughout this chapter to illustrate differences in the developing South and industrialised North (see Chapter 7 for definitions).

9.2.2 The Carbon Correlating Equation

The significance of the four variables to the *per capita* national carbon footprint was assessed using 'power-law correlation' techniques. In order to determine the strongest dependency each of the variables were originally plotted against *cf.* It was shown that economic wealth offered the strongest direct correlation with the carbon footprint (Figure 9-1), where $a = 1$. This was to be expected as the footprint is a purely consumptive driven indicator; those nations with larger incomes and successful economies inevitably emit a larger magnitude of emissions. Some nations are more environmentally conscious than others; see for example Figure 9-1 where Germany and Australia, of the high income countries, can be highlighted as being below the correlating line. It must be recognised that with growing consumptive patterns carbon emissions will continue to rise (see Chapter 11).

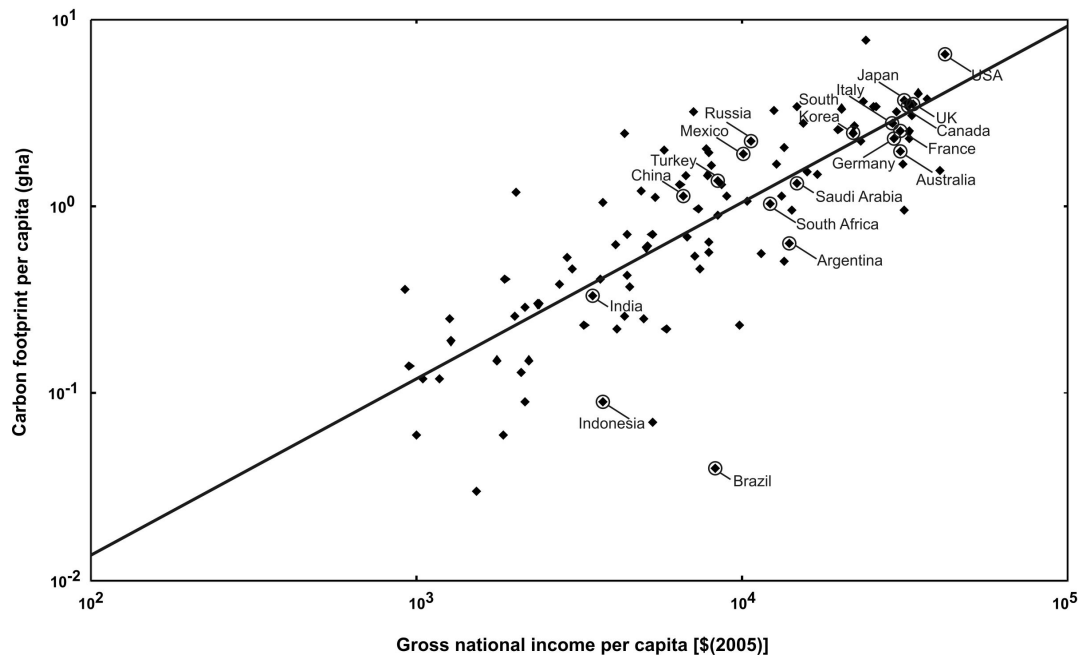


Figure 9-1: Variation of *per capita* national carbon footprints with economic wealth across nation states of the world in 2005
(G-20 nation states highlighted)

The remaining three parameters in equation 9-1 were considered with respect to both economic prosperity and carbon footprint, to ensure no interdependence. Naturally carbon ratio and carbon footprint are linked, since the amount of carbon emitted per joule must be reduced in order to lower the carbon footprint of a country. With improving technologies, better efficiencies and energy intensities this may be possible as we head towards a low carbon future.

It has previously been shown (see Chapter 8) that energy and carbon total values are strongly related to economic wealth for the year 2003. However, in this updated study, analysing the year 2005, it was shown that CR and EI should not be eliminated from the correlating 'power-law' equation (see section 9.3). It was important to include these variables, for both the carbon and ecological footprint analyses, particularly given the improvements in energy use and carbon reductions that were considered into the future as demonstrated in Chapter 10.

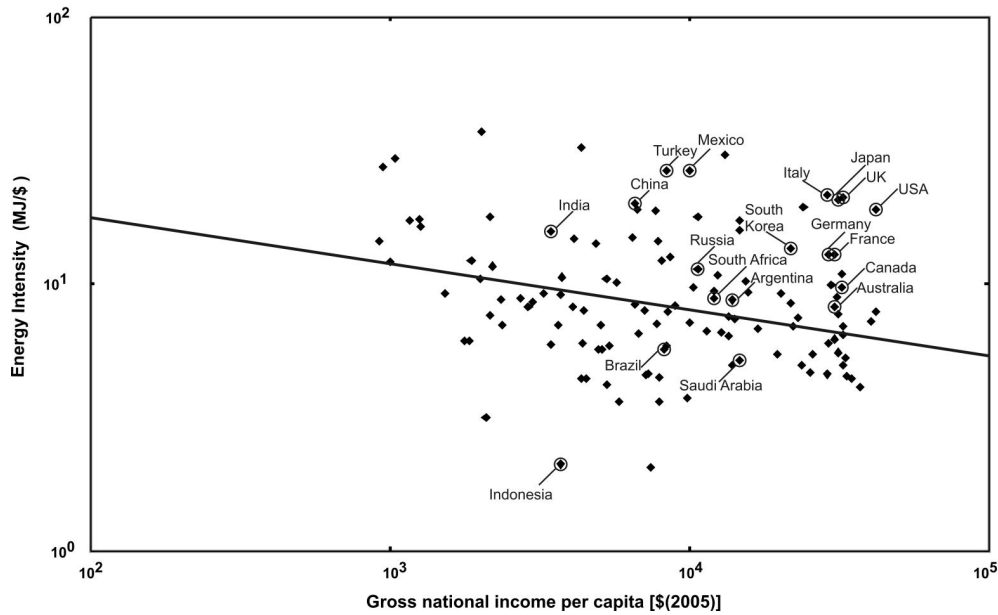


Figure 9-2: Contrasting energy intensity with affluence of nation states throughout the world for 2005
(G-20 nation states highlighted)

The relationships between these additional factors and economic wealth are shown in Figure 9-2 and Figure 9-3. It is debatable whether any correlation is justified with such a wide scatter; however it is considered that energy intensity tends to decrease with higher levels of affluence, in a similar manner to that discussed in Chapter 8. This highlights a move towards service based economies in high income countries away from energy intensive industries. The carbon ratio increases slightly with economic welfare (Figure 9-3), indicating that despite improvements in efficiencies and carbon reducing strategies, the amount of carbon emitted per joule does not decrease with wealth. This data is only shown for the year 2005, and may change over time as technological advances are implemented into the future (see Chapter 10).

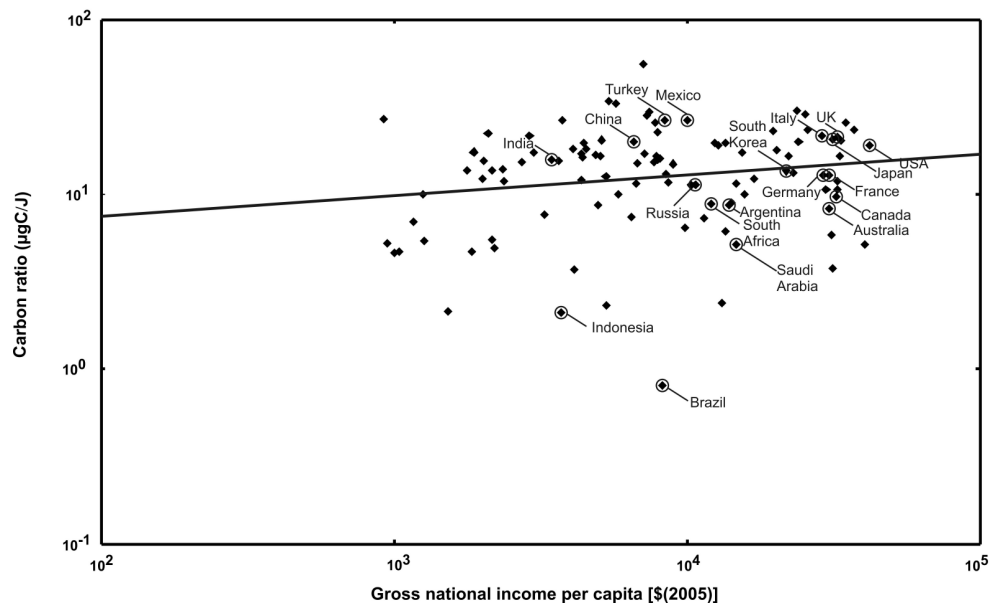


Figure 9-3: Comparing carbon ratio for various countries with their respective economic welfare
(G-20 nation states highlighted)

Having established the relationship between the *per capita* carbon footprint and economic growth (Figure 9-1), it was necessary to combine these factors and assess them with regard to the remaining determinants – energy intensity and carbon ratio. It was ascertained that carbon ratio had the best correlation with these parameters, with an exponent $d \approx \frac{3}{4}$ (Figure 9-4). These results were combined in order for energy intensity to be evaluated.

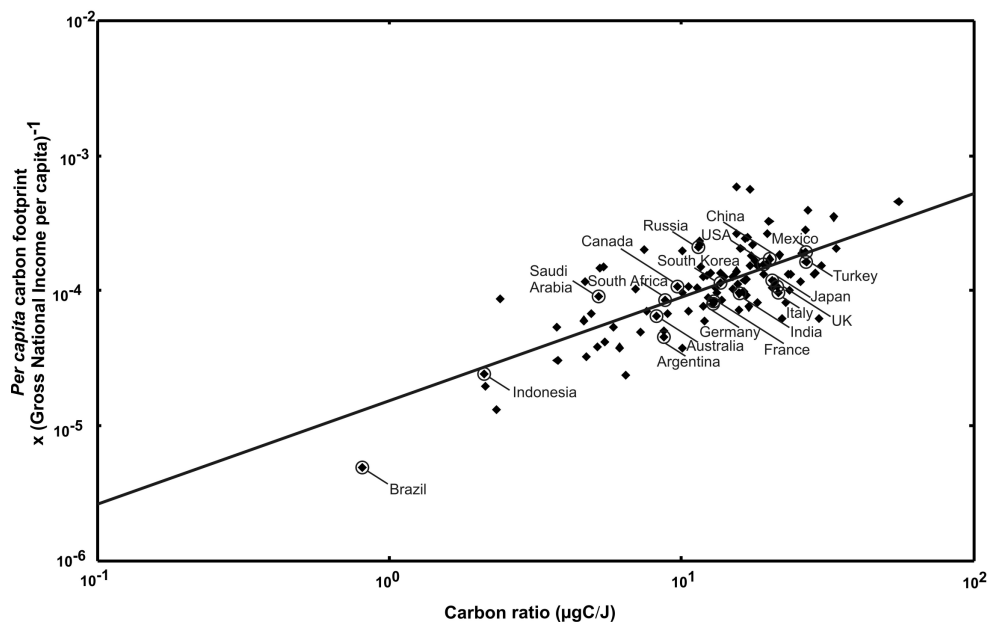


Figure 9-4: Relationship between *per capita* carbon footprint, economic wealth and carbon ratio
(G-20 nation states highlighted)

The final result showed that energy intensity and carbon ratio were both important factors related to the carbon footprint, such that $c = 1$ and $d = \frac{3}{4}$ (Figure 9-5). This offers some optimism for the future. As countries move towards better sustainable practise they may improve their energy use and reduce carbon emissions through advancements in technology and efficiencies. Countries still developing could be encouraged to reduce their emissions by adopting proven technologies from other nation states. This will impinge on the energy intensity and carbon ratio values and thus result in a decreasing carbon footprint for the future.

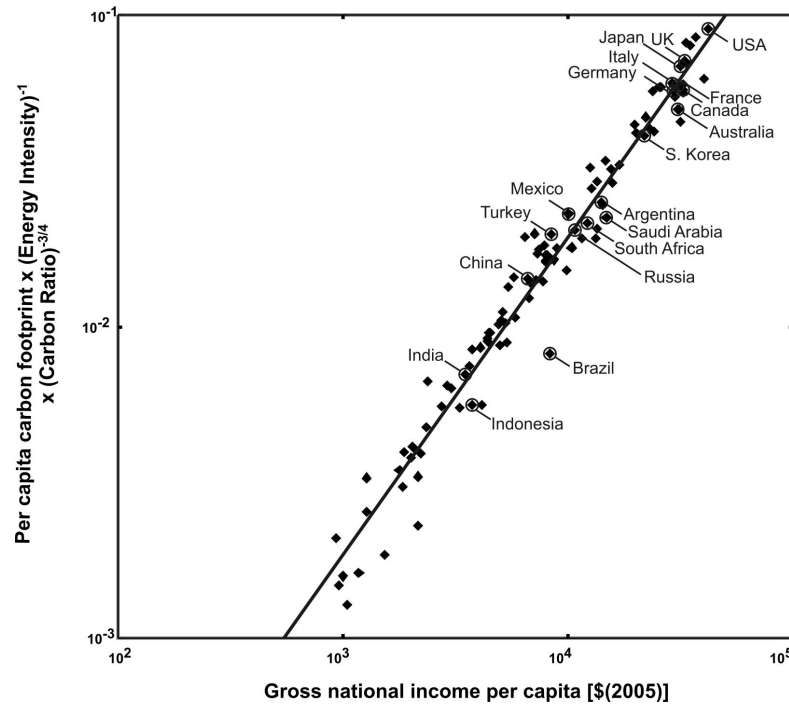


Figure 9-5: Carbon footprint relationship to economic wealth, energy intensity and carbon ratio around the world
(G-20 nation states highlighted)

Population density showed a very poor correlation, with its exponent $b \approx 0$, and was therefore eliminated from the 'power-law' equation in the same manner as other determinants discussed in Chapter 8. Substituting all the exponents for the variables into the original cf expression (equation 9-1), the final 'power-law' correlation was obtained (equation 9-2).

$$cf = 2 \times 10^{-6} \times GNI \times EI \times CR^{3/4} \quad 9-2$$

This equation describes how the *per capita* carbon footprint is heavily dependent upon economic wealth and energy intensity, and strongly related to carbon ratio (Figure 9-5).

The G-20 nations (see Chapter 7) were highlighted and it can be seen which countries are frugal or profligate in terms of their carbon emissions and consumption (Figure 9-5). Those above the correlating line are considered to be wasteful in terms of their resource

use, whilst those below it are more frugal. As expected, the developed countries were clustered at the top end of the plot, mostly sitting on or near the correlating line. Australia was the only nation with a slightly more conservative result. The developing nations were further down the plot and relatively more spread out. Of the G-20 nations, those considered to be developing were far more sparing of their natural resources, particularly Indonesia and Brazil. Those more 'transitional' countries were placed in the middle, whilst those in early development stages were lower down according to their economic state. It could be seen that those developing countries in the G-20 were, on balance, more frugal than the industrialised regions. Research has shown that this may not always be the case as they move towards industrialisation and urbanisation (Cranston & Hammond, 2010b) (see also Chapter 10). It is therefore crucial that green technologies and good practice are passed onto these nation states to prevent carbon emissions escalating to intolerable and irreparable levels. Countries such as China and India may not yet have the economic affluence of the developed world, but their consumption and waste emission patterns, in terms of the carbon footprint, are slightly profligate (Figure 9-5). This trend and influence will change as we head further into this century; it is true for the ecological footprint as well as the carbon footprint. It is important that world leaders are willing to encourage the developing countries to strive towards environmental policies and support them by the sharing of knowledge and experience.

9.3 UPDATING THE ECO FOOTPRINT CORRELATION

Cranston *et al.* (2010) developed a 'power-law' correlating equation relating *per capita* national ecological footprints to economic prosperity and population density (detailed in Chapter 8). This analysis was repeated in this chapter using the most up-to-date data for the year 2005 in order to compare and contrast the correlating carbon equation with the equivalent ecological footprint power-law (Cranston & Hammond, 2010c). Many driving forces that had previously been considered as determinants for the ecological footprint in the year 2003 had been eliminated from the correlating equation, and the relationships with these factors were so weak that they were not considered in this updated study. Thus the initial expression was in the form:

$$ef = \text{constant} [(GNI)^p (PD)^q (EI)^r (CR)^s] \quad 9-3$$

The relationship between economic growth and *per capita* ecological footprint was once again shown to be the strongest (Figure 9-6) with the exponent $p = 2/3$.

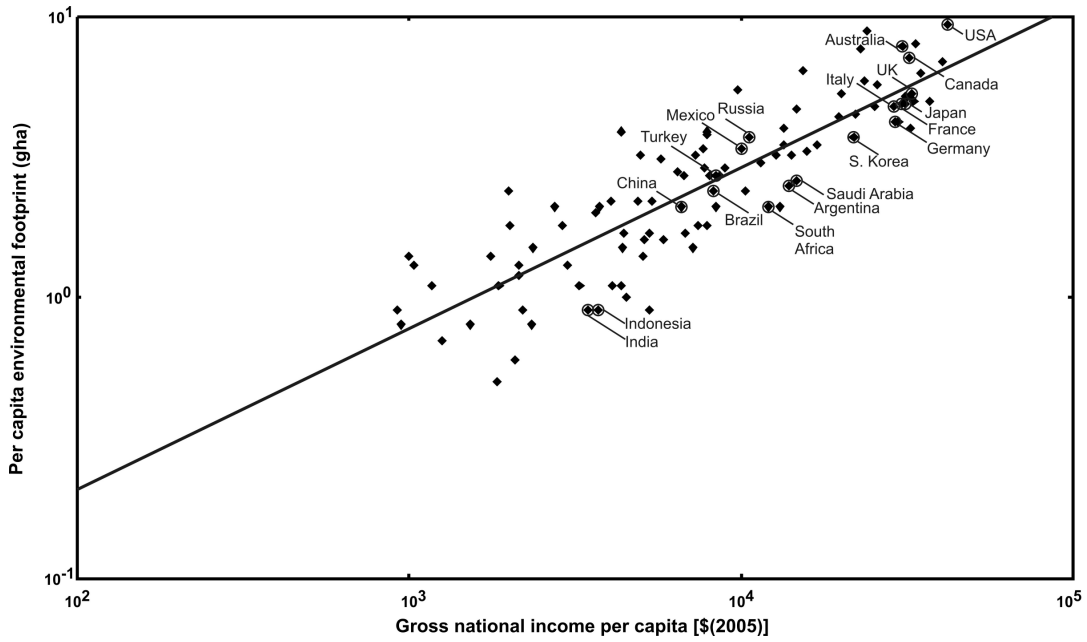


Figure 9-6: Relationship between *per capita* ecological footprint and national income for the year 2005
(G-20 nation states highlighted)

In this updated study for the year 2005, the energy intensity and carbon ratio values were not eliminated, but had strong enough correlations to warrant inclusion in the final equation. The relationship between economic welfare and both energy intensity and carbon ratio is discussed in section 9.2.2. The inclusion of these variables can be explained since the data was more recent, and improvements in energy use and carbon efficiencies have begun to be implemented, thus impacting upon the footprint values in a more significant manner. It also allowed a fair comparison between the correlating equations for the carbon and ecological footprints. Population density still had a small influence upon the footprint, and through its inclusion provided a better correlation within the final equation.

The final equation was proven to be:

$$ef = 0.0020 \cdot GNI^{2/3} \cdot PD^{-1/10} \cdot EI^{1/4} \cdot CR^{1/5} \quad 9-4$$

This correlation will vary over time, as improvements in energy use, changes in the energy mix and international development come to the fore. Such scenarios are discussed in Chapter 10. Multi-linear regression (see Chapter 7) was used to validate this result as detailed in equation 9-5.

$$ef = 0.0042 \cdot GNI^{0.5986} \cdot PD^{-0.1158} \cdot EI^{0.2398} \cdot CR^{0.1859} \quad 9-5$$

The resultant exponents from multi-linear regression were considered to have too many significant figures than is appropriate given the accuracy of available data. Instead the fractional exponents in equation 9-4 were adopted, in line with standard notation from dimensional analysis (Chapter 7). The similarities between these values are highlighted in Table 9-1.

Parameter	Multi-linear Regression Exponents	Exponents with appropriate significant figures	Dimensional Analysis Exponents
<i>GNI</i>	0.5986	$0.6 \approx 2/3$	$2/3$
<i>PD</i>	-0.1158	$0.1 \approx -1/10$	$-1/10$
<i>EI</i>	0.2398	$0.25 \approx 1/4$	$1/4$
<i>CR</i>	0.1859	$0.2 \approx 1/5$	$1/5$

Table 9-1: Comparison of correlating ‘power-law’ equation exponents

The correlating ecological footprint equation can be represented graphically in Figure 9-7, where the G-20 nation states are highlighted. As was discussed in Chapter 8, the location of countries about the correlating line demonstrates their profligate or frugal tendencies towards Nature’s resources. In a similar manner to the 2003 case, the developed world is focused about the upper end of the correlating line. The developing countries are far more spread out, representing not only their differing stages of development, but also their use of natural capital. Countries such as Brazil appear to have excessive use of resources, but this must be considered alongside the nation’s poor use of energy efficient technologies and limited access to carbon reducing strategies. This result is biased by the fact that the calculation for the carbon footprint in the *Living Planet Report 2008* is most likely an underestimate (Reed, 2008). This impacts the results for carbon ratio as well as the final correlating equation. The carbon emissions estimate for Brazil has not significantly changed between the 2006 and 2008 editions of the National Footprint Accounts, so the source of the discrepancy is likely in the calculated embodied energy in trade flows. It was thought that the underestimate of Brazil’s carbon footprint is a result of overestimating the embodied energy in exports (Reed, 2008).

China is in line with the correlating trend, but over time it can be predicted that such emerging economies may rapidly expand with overuse of natural resources and less consideration for environmental development. These issues are presented, analysed and discussed in Chapter 10.

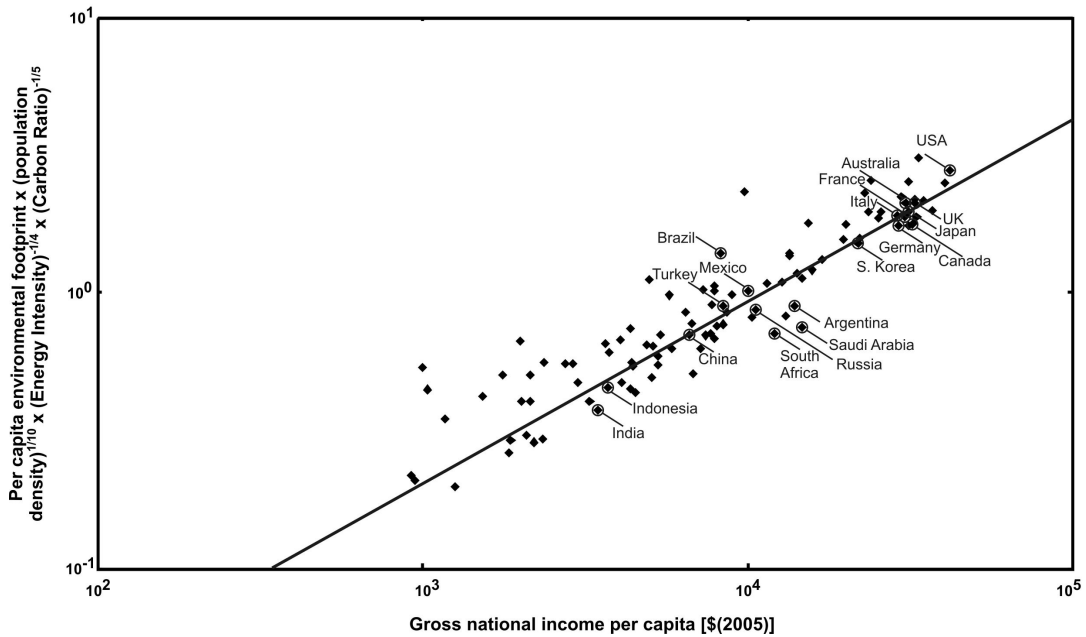


Figure 9-7: Per capita national ecological footprint correlating equation
(G-20 nation states highlighted)

This updated ecological footprint equation was compared to the final carbon footprint equation (Figure 9-8). Both equations have similar final results, where economic wealth dominates the footprint in each case; however, the exponents of such parameters vary between these two indicators. The exponent for affluence is larger for the carbon footprint, which illustrates that this energy based footprint is even more dependent upon economic welfare than the ecological footprint. This result is intuitive, since those more wealthy countries have larger carbon footprints (see Figure 9-1) due to the availability of, for example, energy services and transportation. The relationship between carbon footprint and both energy intensity and carbon ratio is stronger than with the ecological footprint. This is due to the significant impact the improvements in energy efficiency and carbon reduction strategies may have upon the final carbon footprint. Such developments will primarily affect energy use which is associated with carbon emissions, and therefore the carbon footprint. The carbon footprint represents a major segment of the ecological footprint (Ewing *et al.*, 2008b) and it was expected that these advancements would also influence the ecological footprint, but less strongly, as suggested by equation 9-4.

Figure 9-8 shows the similarity in trends across the prosperous North and the populous South in terms of environmental and carbon footprints. For both of these indicators, the industrialised world is grouped about the upper end of the correlating line, representing a common use of resources and efficiencies. The transitional economies tend to be more scattered. Brazil can be highlighted as having significantly different trends for its carbon and ecological footprint. This is due to its relatively low carbon usage which is reflected in its below average trend for the carbon footprint in the region of similar economically developing countries. However, the ecological footprint

considers a variety of factors, not focused purely on carbon. The carbon footprint is more limited in scope, and the correlating equation includes energy intensity and carbon ratios where Brazil is less successful, resulting in a different position in relation to each correlation. Issues with data regarding Brazil have been discussed above.

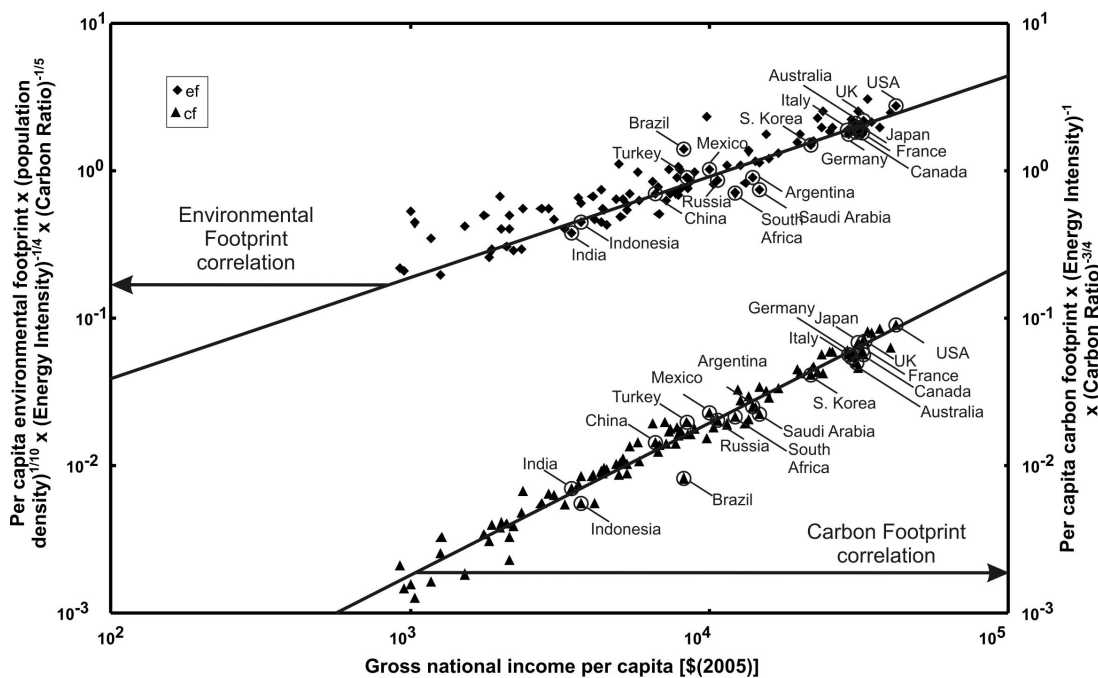


Figure 9-8: Comparison of environmental and carbon footprint correlating equations
(G-20 nation states highlighted)

It is vital that a nation state aim to reduce their resource use and emissions to an appropriate share of the world's biocapacity (see Chapter 4 for details about biocapacity). Through improving energy use and decreasing carbon emissions many more countries could find themselves below the correlation line. Figure 9-9 illustrates the disparity between a selection of countries in terms of their carbon footprint and available biocapacity. The total biocapacity available per person for 2005 was 2.1 gha. Given that the carbon footprint represents approximately 50% of this value on a global average (based on the *Living Planet Report 2008* (WWF International, 2008)), this leaves 1.05 gha that an individual may use in that year after the sequestration of carbon. Many populations are using well above this level. The world cannot continually support this ecological debt as its natural resource 'overdraft' diminishes. Such demands upon the ecosystem are unsustainable as the planet can only regenerate its resources at a certain rate. It is therefore important that strategies to reduce the impact on the biosphere are implemented by the industrialised world and encouraged among the developing nations. If this issue is taken seriously and continues to remain high up on the current political agenda, the demands on Nature may become reasonable as the global carbon footprint reduces. Scenarios have been developed to consider the variety of pathways nation states may tread and how deep the resulting footprints may be (Cranston & Hammond, 2010b) (Chapter 10).

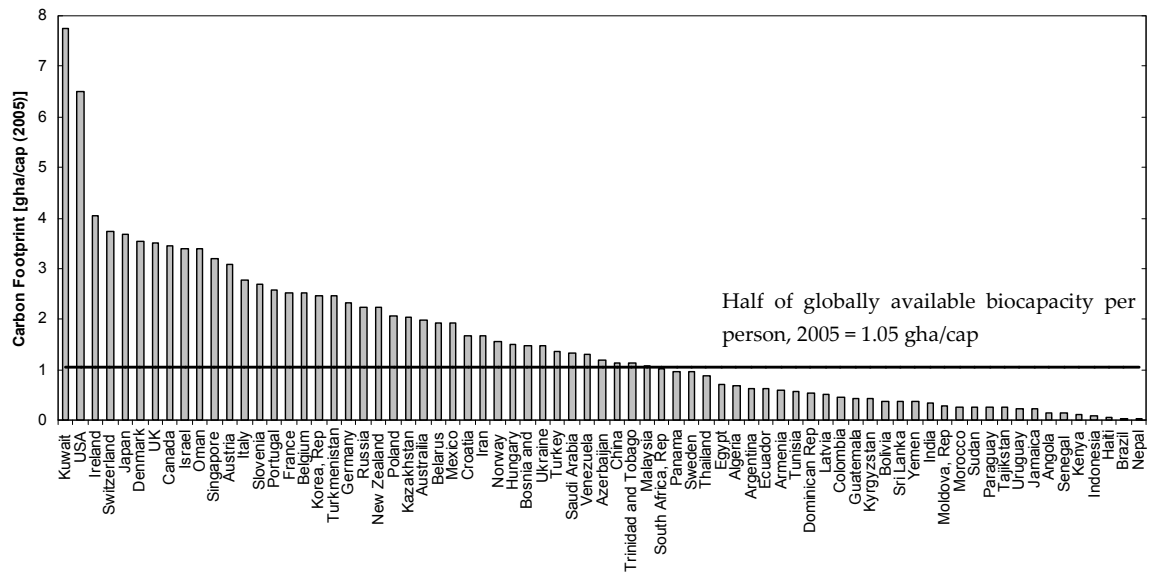


Figure 9-9: The imbalance between per capita carbon footprint of selected nation states and globally available biocapacity

9.4 LOSING WEIGHT THE CARBON WAY

The popularity of the ecological footprint has been overtaken by the carbon footprint. For some, the carbon footprint is now an every day consideration; whether it be in offsetting flights or purchasing energy saving light-bulbs, the general public is becoming more serious about reducing their carbon footprint. This is all very promising, but the use of the term 'carbon footprint' can be misleading. This term has been adopted for a variety of different analyses, ranging from the standard footprint using global hectares, to including CO₂ in terms of a mass to encompassing all GHGs. The carbon footprint is rooted within the ecological footprint, but is now very confused with no clear definition. Wiedmann and Minx (2007) suggested a singular definition based upon a mass, or weight that focuses purely upon carbon emissions. This is laudable, but such a singular definition has not been significantly adopted by either academics or businesses. It completely separates the carbon footprint from any true meaning or function of the fundamental footprint. Hammond (2007b) stated the requirement to be precise when referring to the carbon footprint to improve public understanding. It was therefore necessary to undertake an analysis to compare and contrast these different measures and to determine which may be more useful or indeed applicable within the research remit (Cranston & Hammond, 2010c).

A footprint is fundamentally measured in spatial units of global hectares, but the carbon footprint so often referred to is actually a 'carbon weight', so called in this chapter, of kilograms per person or activity (Hammond, 2007b). This represents a total mass of carbon, and as such is not the spatial indicator measured in global hectares that defines the footprint. As the methodology for carbon footprinting may not be perfect (see Chapter 3), it is perhaps not surprising that 'carbon weight' has become more

acceptable in the public domain, since its formulation is far less controversial and requires no conversion to a spatial unit. However, it is far more likely that the reason a carbon weight term is adopted is that the carbon footprint is not fully understood and its benefits and simple, contextual units are ignored. Even the WWF's *Living Planet Report 2008* has acknowledged that the term 'carbon footprint' has been misused by many, calculating tonnes of carbon or tonnes of carbon per Euro, rather than the demand on bioproductive area (WWF International, 2008). Indeed, many organisations have adopted the use of the term carbon footprint when assessing the carbon dioxide emissions released during associated processes or activities but these are measured in tonnes of carbon dioxide (for example, BP (2009) and Directgov (2009)). This is highly confusing and detracts from the important, fundamental meaning of the footprint. Kitzes and Wackernagel (2009) suggested that the carbon footprint measured in global hectares adds value to carbon emissions in two ways: the first being that it puts emissions into a context that is far more meaningful to the general public – in spatial units that compares our consumption to the available resources supplied by Nature. The second is that using the correct terminology also enables a comparison to other demands on productive land. This is far more useful as it allows assessment of other energy based solutions, such as the growth of biofuels, with respect to the effects this change will have upon the biosphere and its biocapacity. Clarification between the carbon footprint and carbon weight is necessary; this chapter aims to show the differences between these two indicators.

9.4.1 How heavy is our footprint? Treading lightly...

The carbon weight or 'carbon consumption' for 107 nations was calculated and compared with their respective carbon footprint. The carbon weight, C_W , values were calculated from carbon dioxide data per country, based upon consumption and waste assimilation for its population, and excluded the emissions released in producing goods that were exported and used in other countries. This is an approximation based upon international statistics. The adjustment from carbon production to carbon weight is described by equation 9-6. This calculation was necessary to ensure compatibility between the carbon footprint detailed in the *Living Planet Report 2008* (WWF International, 2008) and not only the carbon weight discussed in this section, but also the carbon ratio utilised in section 9.2.

$$C_W = C_P + C_I - C_E + C_B \quad 9-6$$

Where C_W	Carbon Weight
C_P	Carbon Production
C_I	Carbon from imports
C_E	Carbon from exports
C_B	Carbon from bunkers

International Marine and International Aviation Bunkers contain emissions from fuels burned by sea-fairing ships under all flags and aircraft that are engaged in international transport. This value was added to the consumption value to take account of each nation's contribution to international transport (Kitzes *et al.*, 2008b). A percentage between 3-4% of total carbon dioxide emissions is standard (Kitzes *et al.*, 2008b) and in this case a value of 3.27% was chosen from the 2008 Global Footprint Accounts (Global Footprint Network, 2008c).

The trade corrected data was collected for 627 commodities for each country for their imports and exports from the UN Statistical Division – UN Comtrade (UNSD, 2009)³. These traded commodities were established by their SITC (statistics of international trade classification) revision 1 codes since this classification system offers the longest historical time series and is used by the leading footprint companies such as Global Footprint Network and Best Foot Forward (Simmons *et al.*, 2006). UN Comtrade is the largest depository of international trade data and has over 140 reporter countries providing annual international trade statistics detailing commodities and partner countries (Vempaty, 2007). All commodities for imports and exports were summed respectively. The trade data was converted from mass in kg to M tonnes of carbon dioxide emissions using specific world average embodied energy provided by the Best Foot Forward report for the WWF *One Planet Business Programme* (Simmons *et al.*, 2006) and conversion factors for world average carbon intensity of electricity and heat production were applied from the Global Footprint Network spreadsheets (Global Footprint Network, 2008c). A final conversion was made from CO₂ to carbon using the molecular balance 12/44 = 0.27. These conversions are further explained in section 9.4.2.

9.4.2 Details of Trade Correction Calculations

The embodied energy of each commodity was taken from the Global Footprint Network's 2008 edition of the National Accounts (Global Footprint Network, 2008c). Embodied energy is the energy required throughout the complete life cycle of a product, from manufacture to transportation to use and disposal. Footprint studies often use this embodied energy when tracking the trade of goods (Global Footprint Network, 2009b). From the UN Comtrade database the net weight in kg of each commodity was established. This could thus be converted to an 'import energy' or 'export energy' using the embodied energy values as shown in equation 9-7.

$$\text{Im port Energy} \left[\frac{\text{GJ}}{\text{yr}} \right] = \text{EmbEn} \left[\frac{\text{GJ}}{\text{t}} \right] \times \text{NetWeight} \left[\frac{\text{kg}}{\text{yr}} \right] \quad 9-7$$

³ Where data from UN Comtrade was unavailable CDIAC values (Marland *et al.*, 2008) were applied in accordance with Global Footprint Network guidelines (Kitzes *et al.*, 2008b).

Import or Export Energy was converted to a mass using the world electricity and heat carbon intensity from the Global Footprint Network and the ratio of Gigajoules of energy to Terawatt Hours (Global Footprint Network, 2008c) (equation 9-8).

$$\begin{aligned} \text{ImportCO}_2 \left[\frac{\text{MtCO}_2}{\text{yr}} \right] &= \text{ImportEnergy} \left[\frac{\text{GJ}}{\text{yr}} \right] \\ &\quad \times \text{Gigajoule to Terawatthour conversion} \left[\frac{\text{TWh}}{\text{GJ}} \right] \\ &\quad \times \text{World Elec\& Heat Carbon Intensity} \left[\frac{\text{MtCO}_2}{\text{TWh}} \right] \end{aligned} \quad 9-8$$

Finally the values of Import and Export CO₂ were converted to carbon based upon molecular weights.

CO₂ production from the burning of fossil fuels was taken from the International Energy Agency (IEA, 2008). The Sectoral Approach was chosen to ensure comparability with the WWF's *Living Planet Report 2008* (WWF International, 2008) and accepted footprinting methodologies (Simmons *et al.*, 2006). The Sectoral Approach calculates CO₂ emissions from fuel combustion based upon the main fuel combustion activities of that country, such that emissions are broken down in terms of sectors. This offers more detailed calculations than were used for the Reference Approach where total CO₂ emissions were established purely from fuels supplied to a nation.

Once the carbon weight was calculated for an individual country it was converted to a carbon footprint. This was verified by assessing the differences between the resulting carbon footprint and that given in the *Living Planet Report 2008* (WWF International, 2008). The calculated results had an average percentage difference of only 4.8% to those presented by the WWF.

Carbon weight was converted to carbon footprint using equation 9-9, which is based upon the Global Footprint Network's *National Footprint Accounts 2008* (Global Footprint Network, 2008c)

$$\begin{aligned} cf &= \frac{(C_W) [\text{Mt CO}_2/\text{yr}] \times (1 - \text{Ocean Sequestration})[\%] \times \text{Forest EQF} [\text{gha/ha}]}{\text{Carbon Sequestration} [\text{t CO}_2/\text{ha} \cdot \text{yr}]} \\ &= \frac{(C_W) \times (1 - 0.25) \times 1.33}{0.97} \end{aligned} \quad 9-9$$

Carbon sequestration, or 'carbon uptake rate', is the annual rate of carbon uptake per hectare of world average forest land; it was derived from data on the net annual growth of forests. The forest equivalence factor converts the forest land to the common unit of global hectares (details of equivalence factors and the global hectare can be found in Chapter 3). Carbon sequestration and forest equivalence were both taken from the

National Footprint Accounts 2008 to be 0.97 tC ha⁻¹ yr⁻¹ and 1.33 gha ha⁻¹ respectively (Global Footprint Network, 2008c).

9.4.3 Close Relationship for Carbon Footprint and Weight

The relationship between the carbon footprint and carbon weight measures were compared, having established the values for the carbon weight, and verified them with respect to the *Living Planet Report 2008*. The conversion between these two factors, as defined in this chapter, was approximately one (equation 9-10); as such the footprint and weight returned very similar results (see Figure 9-10). This could be considered as very convenient as it may aid those who fully understand the footprinting concept to readily convert the 'carbon weight' to a carbon footprint.

$$\frac{cf}{C_W} \approx 1 \quad 9-10$$

It must be pointed out at this juncture, however, that this simple conversion will not always be so straightforward since many analyses use different assumptions in their makeup and development of the carbon weight value. Not all companies use trade corrected data but consider only the direct carbon emissions, others may look at carbon equivalent values or try to include a host of GHGs within the indicator (Wiedmann and Minx, 2007). The conversion used here is appropriate since when formulating the carbon weight the methodology for the formation of the carbon footprint was carefully followed, to ensure compatibility between the two indicators and enable the analysis undertaken in this chapter.

Figure 9-10 shows the carbon footprint and carbon weight plotted against economic welfare. The G-20 nation states are highlighted and it can be seen that the prosperous countries of the North are located at the top end of the plot in terms of both the carbon weight and carbon footprint. Those more transitional economies are in the mid range, whilst the developing countries such as Indonesia and Brazil⁴ are further down the figure. This pattern was to be expected given the progress of development for each country and the general relationship between economic advancement and subsequent emissions.

⁴ Must consider the issues surrounding the lower than expect carbon footprint for Brazil, its value should be larger and thus more in line with the trends.

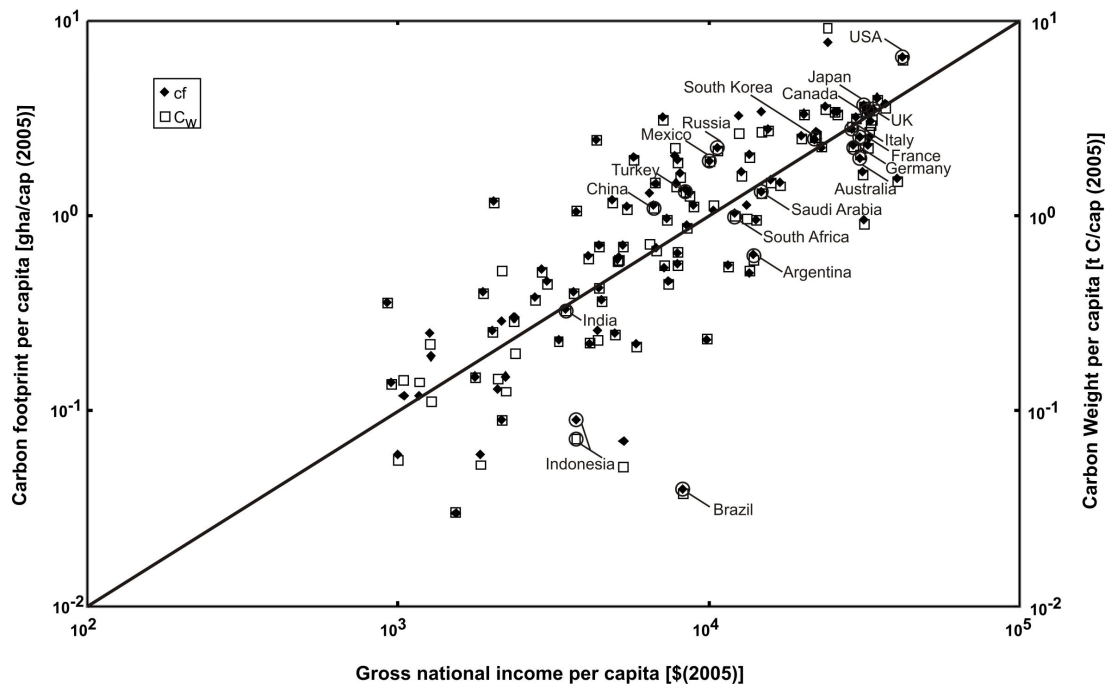


Figure 9-10: Comparison of Carbon Footprint and Carbon Weight for nation states around the world for the year 2005
(G-20 nation states highlighted)

The correlating 'power-law' equation that has been established in section 9.2.2 was adapted for the carbon weight, such that the equation for carbon weight included the appropriate multiplying factor to convert from carbon footprint:

$$C_w = 1 \times (2 \times 10^{-6}) \text{ GNI} \times \text{EI} \times \text{CR}^{3/4} \quad 9-11$$

The carbon weight and carbon footprint values were again compared with respect to the 'power-law' correlating equation result (Figure 9-11). This figure shows how well correlated both these functions are, and upon considering the G-20 nation states the differences between the industrialised, wealthy North and the developing, populous South can be seen.

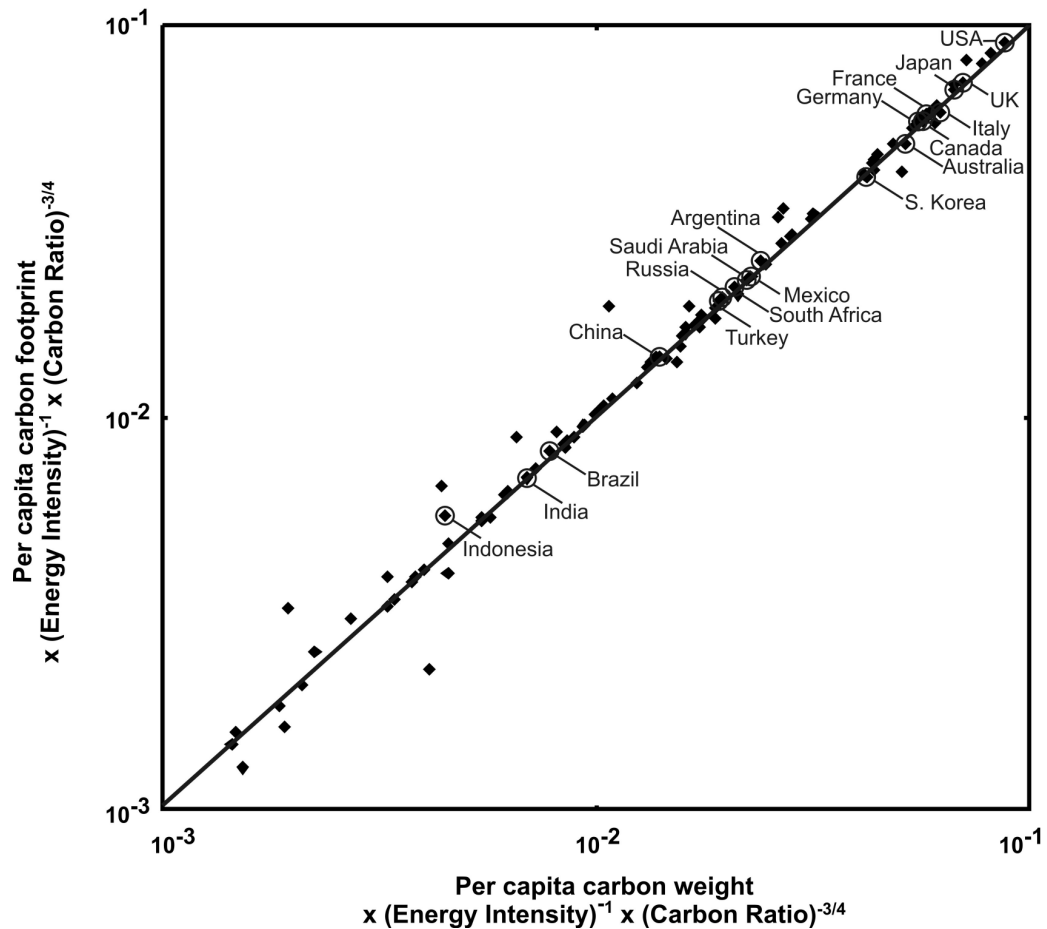


Figure 9-11: Comparison of Carbon Weight and Carbon Footprint equations across the world

(G-20 nation states highlighted)

The carbon footprint has been shown to be a popular tool and one that is used regularly in the media. However, it has often been misinterpreted, and is used as a mass rather than a spatial indicator. By comparing the carbon footprint and carbon weight it has been deduced that they are very similar in magnitude, with a conversion factor of 1. Perhaps the argument about using carbon footprints or carbon weight is therefore made redundant as they are both essentially stating the same point and being used as a tool to highlight our excessive carbon emissions and consumptive patterns. The only key difference is that carbon weight or consumption doesn't relate this to natural capital and the limited biocapacity available per nation state or indeed per individual, thus given a poor indication of ecological deficit due to carbon emissions. This carbon footprint indicator is something that people can more readily relate to and understand than a mass that really bares little significance on their lives and has no relative value. Stating a person has already used 80% of their 'Earthshare' half way through the year may be a much more effective way of portraying the problem and our attitude towards our personal contributions to environmental degradation.

9.5 SUMMARY

Carbon footprints have caught the attention of the world and have stirred many into a frenzy of carbon reducing action. Unfortunately the common portrayal of the carbon footprint is not a footprint at all, but a mass. This chapter considers the significance of this difference and the importance of the carbon indicator; it is shown that the carbon footprint and carbon weight are very similar in magnitude, with a conversion factor of approximately 1. Alongside this, the influence of economic wealth, population density and pollutant emission intensity upon the carbon footprint are considered and developed into a correlating 'power-law' equation, building upon the work of Cranston *et al.* (2010) (Chapter 8); all such variables, with the exception of population, were proven to be significantly impactful upon the carbon footprint. These studies are innovative since such detailed analysis behind the makeup of the carbon footprint has not previously been undertaken.

The way in which countries are wasteful or frugal with their resource use is illustrated by highlighting the G-20 nations. The carbon footprint was proven to be dependent upon economic wealth, but also strongly related to energy intensity and carbon ratio. Therefore methods and policies to improve these ratios could lessen impacts upon the biosphere and reduce the level of carbon emissions. It is down to the economically prosperous to lead the way, and pave the pathway for transitional and developing countries to follow.

The necessity to aid the developing world as they move towards industrialisation is also discussed in view of the results. As the transitional countries grow in geopolitical power and become key economic players, it becomes important to consider how best to implement action against climate change. There must be a commitment from both the industrialised and developing world which can be implemented through post-Kyoto negotiations.

Aim 1 is completed through the development of a correlating equation not only for the ecological footprint but also for the recently popularised carbon footprint. This is realised through the implementation of objective 5 and analysing the key determinants behind the footprint and assessing them using appropriate analysis techniques.

CHAPTER 10

FOOTPRINT FUTURES FOR THE NORTH AND SOUTH

10.1 INTRODUCTION

It is important for developed, or industrialised countries (in the prosperous North) to play their full part in maintaining environmental sustainability as they currently emit the bulk of pollutants into the atmosphere (Hammond, 2000). However, it is vital that sustainable development also be viewed in a global context. The task facing the nearly 80% of the world population that live in developing countries (the majority South) is daunting and economic development would benefit from, perhaps even require, fairer terms of trade between the OECD and developing countries. Environmental sustainability could therefore be aided by the transfer of best practice energy technologies from the richer to poorer regions. This will ultimately be in the interests of all the citizens of 'Spaceship Earth' (Hammond, 2000).

The ecological footprint is traditionally used to give a 'snapshot' of a population's demands upon Nature for a specific year. Indeed, the relative use of natural capital for nation states was highlighted in Chapters 8 and 9, with a focus upon the G8+5 and G-20. It was evident that there was a clear discrepancy between the industrialised North and the developing South. However, this result was indicative of only one year, and it has often been mooted that the balance between the developing and industrialised world may begin to shift in the future. The relative contributions of the peoples of the industrialised North and populous South up to 2100 was considered by Cranston & Hammond (2010b) and is detailed within this chapter, using the correlation equation for national ecological footprints alongside international projections of population growth and gross regional income and is discussed within this chapter. By applying the correlating equation and developing it with respect to the IPCC scenarios, objective 6 was completed; future pathways for the developed and industrialising worlds were established up to 2100. This led to fulfilling Aim 2, where these two worlds are compared and contrasted into the future. The correlating equation was developed to account for future changes, for example in energy use, up to 2100; the change from the 2003 situation to 2100 had to be accounted for by bounding the two core equations to yield a smooth transition.

Making projections of total global and regional footprints into the future, alongside other development indices (like population and economic well-being) is complex. Hammond (2006a) developed a correlating equation that relates the *per capita* ecological footprint of nation states to their population density and economic wealth. This expression was subsequently revised by Cranston *et al.* (2010), which is detailed in

Chapter 8, based on more recent data and a wider range of independent variables. This equation has been employed here, together with international projections of population growth and of gross regional income, in order to estimate the relative size of footprints for the prosperous North and the populous South up to 2100. Chapter 7 outlines the split between the affluent North and the majority South.

The purpose of this study and this chapter was to establish future ecological footprint values for the developing and industrialised region of the world up to the year 2100. Future footprints have previously been estimated by the bodies such as the WWF within their *Living Planet Report 2008* (WWF International, 2008) and the World Business Council for Sustainable Development's (WBCSD) *Vision 2050* project (WBCSD, 2010). However, these tend to follow the 'return to sustainability' and 'business as usual' scenarios. They therefore differ significantly to the IPCC scenarios that do not favour any one scenario and offer a selection of varying future alternatives. Vision 2050 in particular breaks down the individual components of the footprint, assessing the changes that will occur within each segment if humanity continues along its current trajectory and what can be achieved if the WBCSD vision is followed up to 2050. This is discussed on a global level, based upon medium population growth, carbon reductions, improved forest yields and increased average crop yields. There has been little development regarding footprint scenarios for the two different regions of the world: the developing and developed nation states. The work presented here investigates the changes within these individual regions in terms of their total ecological footprint, following an original and different methodology than that presented by the WWF and WBCSD, with results going beyond their limit of 2050 to the end of the century, utilising the marker scenarios from the IPCC's *Special Report on Emission Scenarios*.

10.2 BOUNDING THE 21ST CENTURY

Footprint values beyond present day are not known accurately. The work undertaken within this chapter establishes four different options for future pathways up to the year 2100 for the industrialised and industrialising worlds. Once the appropriate socio-economic scenarios had been selected (see Chapter 5), the ecological footprint was calculated for the industrialised and developing world. These were based on the four IPCC marker scenarios. The correlating 'power-law' equation (Chapter 8) for national footprints was utilised for this purpose. This formula shows that the main determinants for the *per capita* ecological footprint up to the early years of the 21st Century were population density and economic wealth:

$$ef = 0.0055 \times GNI^{2/3} \times PD^{-1/10} \quad 8-3$$

Here GNI is the equivalent of the 'Gross National Income' for the world or regional populations (in international dollars), and PD is the associated population densities (Cranston *et al.*, 2010; Hammond, 2006a). It has been discussed in Chapter 8 that the

original ecological footprint ‘power-law’ equation from Cranston *et al.* (2010) was updated to include a more appropriate constant. The results displayed and discussed in this chapter utilise this most recent formula. The original equation was adopted in the work of Cranston & Hammond (2010b) to assess future transition pathways towards a low carbon economy across the developing and industrialised countries. However, the results and trends from this work do not differ significantly from those presented within this chapter, and can therefore be considered as equally valid.

In order to extend the footprint estimates into the future, it was determined that this correlating ‘power-law’ equation should be adapted to take account of future possible improvements in energy efficiency and carbon reductions. This involved the extension of the above equation to include Energy Intensity (EI) and Carbon Ratio (CR) as additional variables (Cranston *et al.*, 2010; Cranston & Hammond, 2010b; Hammond, 2006a):

$$ef = K \times GNI^{2/3} \times PD^{-1/10} \times EI^m \times CR^n \quad 10-1$$

The scaling of each SRES marker scenario and associated projections was used to determine a new constant and powers for EI and CR – K, m and n respectively.

Dimensional analysis was undertaken in the same manner as for determining the relationships for the *per capita* environmental and carbon footprint in Chapters 8 and 9. In order to account for the changes in energy use and carbon emissions it was necessary to compare the future estimates from the IPCC scenarios to the parameters already proven to impact the footprint, namely economic wealth and population density. There was no cross correlation or double counting between these determinants; as such both the energy intensity and carbon ratio could be included in the final equations. The results were slightly different for each marker scenario, given the variations in storylines regarding environmental protectionism, development and growth. The range of energy intensity for future worlds was greater for the A1 and B1 scenario groups, due to sharing of ideas and globalisation which enables technological transfer and equality. The A2 and B2 scenario families are associated with more regional and local solutions, therefore resulting in fewer improvements in overall energy efficiency worldwide but instead having a more disjointed world with pockets of developments. Energy intensity was shown to be the strongest factor relating to economic and population growth and was thus included in the equation first (Figure 10-1).

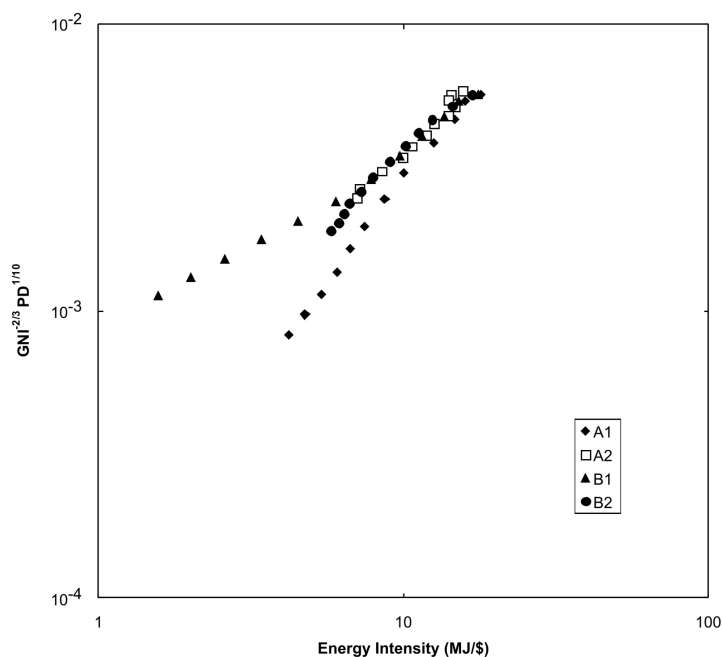


Figure 10-1: Global Energy Intensity Correlation with Economic Prosperity and Population Density for the Four Marker Scenarios

Figure 10-1 shows the correlations between the established economic and population growth with energy intensity for the four marker scenarios, specifically for the world. Energy intensity is well correlated, but offers slightly different relationships for each marker scenario. These results were compared with the carbon ratio values, and showed a further relationship (see Figure 10-2 for example).

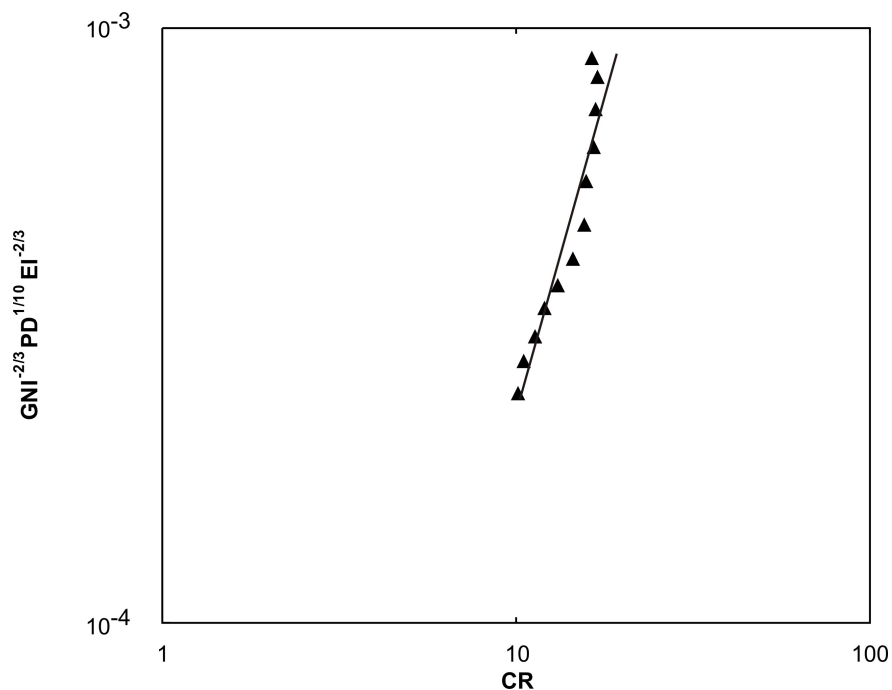


Figure 10-2: Relationship between Carbon Ratio and Future Economic wealth, Population Density and Energy Intensity for the B1 Marker Scenario

The final equations were based upon the parameters shown in Table 10-1. These indicate that the energy intensity is a strong parameter for all the scenarios; if energy efficiency improves it will play an important role in reducing the global footprint levels in the future. The carbon ratio varies more from scenario to scenario. It has a very strong relationship for the B1 storyline, given that this future world is expected to have significant investments and improvement towards environmentally conscious and sustainable living, not just regionally but globally as well. Thus the output of carbon per joule of energy used will be far less, than for instance the A1 scenario family, where there is little focus on reducing emissions but a drive towards economic growth and expansion.

Scenario	m	n	K
A1	4/3	1/10	0.00022
A2	1	1/2	0.00019
B1	2/3	2	0.000007
B2	1	1/8	0.00056

Table 10-1: Parameters for marker scenario equations

The constant, K, was derived by equating each scenario equation with the value for the global footprint in the base year 2003 which was utilised for the original *per capita* footprint equation (see Chapter 8). These derived equations represent the asymptotic conditions for each scenario in 2100, whereas the original expression presented in Chapter 8 was used to represent the 2003 trends. This correlating equation is representative only for the year 2003, whilst the parameters described in Table 10-1 refer to 2100. There was some disparity between the results using these contrasting equations; the shape of the overall trend is considerably different (see Figure 10-3 and Figure 10-4 for example). There was a definitive difference between selecting the original correlating equation for 2003 (equation 8-3, pp.109) or the updated equations for 2100 (equation 10-1).

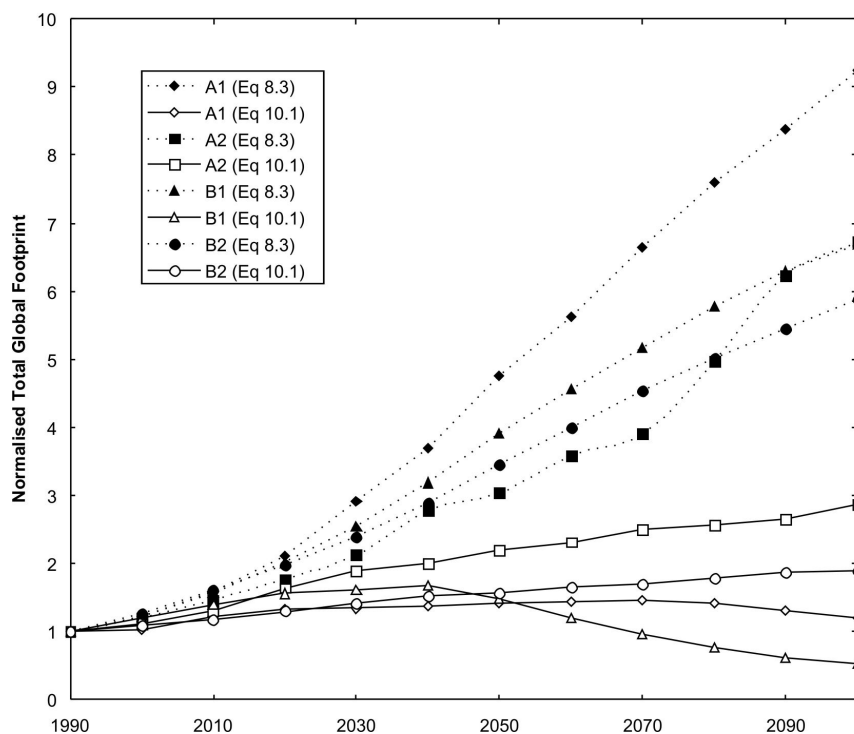


Figure 10-3: Comparison of change in total footprints using two driving equations for the four marker scenarios for the world

The footprints have been normalised to 1 for the base year 1990.

By assuming equation 8-3 the footprint is dominated by economic welfare and growth, and as such the future world has extremely high total footprints. Figure 10-3 highlights the four marker scenarios for the world, and identifies the distinct difference between pathways into the future. Although the scenarios that have been analysed here all have some amount of economic growth, two are also associated with sustainable development and environmental protection. Taking the B1 marker as an example, by applying equation 8-3 it exhibits the second highest growth in global footprint, which contrasts to the results from equation 10-1 where by the end of the 21st century the B1 scenario has the smallest global footprint; in fact it is lower than that in the base year 1990. Following the B1 storyline it was postulated that this scenario would result in a decreased footprint by the turn of the century. It has a moderate level of economic growth which causes the results from equation 8-3, but the results from equation 10-1 are more realistic and in agreement with the SRES storyline by the year 2100.

These resulting differences from the two driving equations are even more noticeable when the developing and developed regions are explored. Highlighted in Figure 10-4 are the A1 and B1 marker scenarios. The results have been normalised in order to compare the data for the developing and industrialised countries. The trends for the results from equations 8-3 and 10-1 are quite different. Applying equation 8-3 shows no reduction in final footprint for either the developing or developed world for all scenarios (see for example Figure 10-4), despite the fact that a decrease is expected for

some storylines; in particular for the B1 storyline, given its environmental tendencies and consciousness regarding reducing emissions.

Adopting equation 10-1 shows an immediate decrease in total footprint for the developed world for both the A1 and B1 marker scenarios, which is highly optimistic and indeed unlikely. For the B1 scenario of the developing world the updated equation 10-1 B1 illustrates the peaking and decreasing tendency by the mid century which reflects the nature of the storyline (Figure 10-4b); the A1 scenario for this updated equation simply flat lines, with a small decrease at the end of the century (Figure 10-4a).

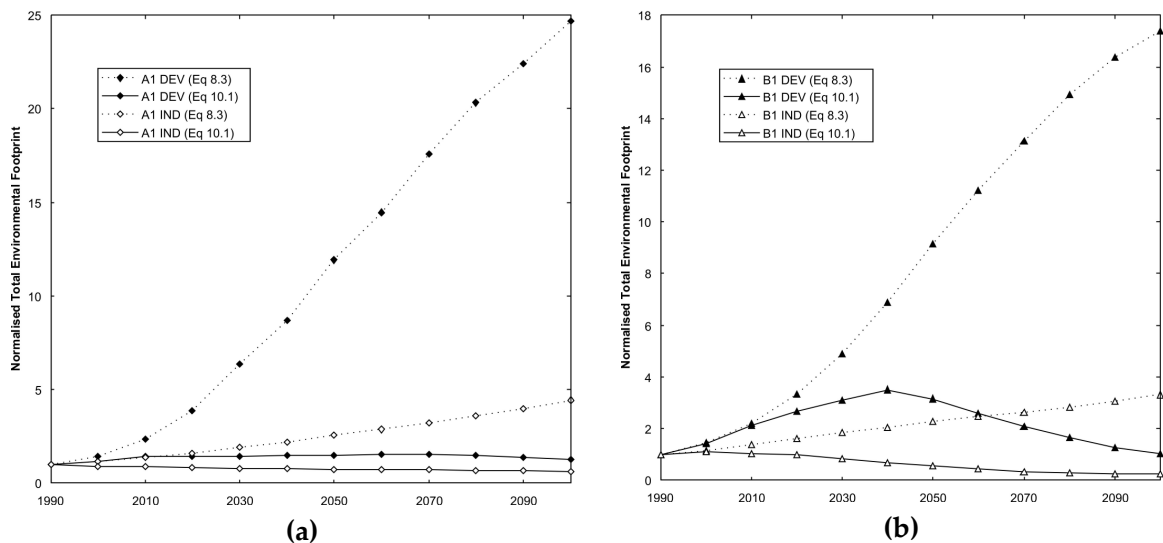


Figure 10-4: Comparison of total ecological footprints for the developing and industrialised world using original and updated equations for (a) A1 marker scenario and (b) B1 marker scenario

The footprints have been normalised to 1 for the year 1990.

Equation 8-3 was optimised only for the year 2003 and it is therefore not appropriate to utilise this equation to represent the entire century. It is unlikely that the trends exhibited by adopting equation 8-3 will hold true up to the end of the century, particularly as they do not account, for example, for developments in energy use and efficiency. The updated equation 10-1 which includes carbon ratio and energy intensity offered an alternative future transition to a far more moderate world accounting for advances in technology, reduced resource use and progression towards efficient and sustainable living, but has been shown to be inappropriate for the entire century, namely the beginning. Therefore it was determined that there needed to be a natural progression from the 2003 correlating equation to the 2100 final relationship which accounts for the gradual improvements in energy efficiencies and carbon cuts for the future worlds.

10.2.1 Modelling the Low Carbon Transition to 2100

The problem of obtaining a correlating equation which will fit between the bounding states (in 2003 and 2100 here respectively) is one of a class of problems in which solutions are known for asymptotically large and small values of an independent variable, namely:

$$y \rightarrow Ax^p \text{ as } x \rightarrow 0$$

$$y \rightarrow Bx^q \text{ as } x \rightarrow \infty$$

where x and y are the independent and dependent variables respectively. Fortunately, Churchill and Usagi (1972) have developed a general solution for this class of problems in the thermal sciences of the form:

$$y = \{(Ax^p)^m + (Bx^q)^m\}^{1/m} \quad 10-2$$

where $m > 0$ if $p < q$, and vice versa. They originally applied this formulation to heat transfer problems involving laminar buoyancy-driven convection, and to laminar, mixed (combined buoyancy-driven and forced) convection. Alamdari and Hammond (1983) employed this interpolation formulae to develop improved, full range correlations (across the laminar, transitional and turbulent airflow regimes) for buoyancy-driven convective heat transfer from the internal surfaces of naturally-ventilated buildings. In a similar way, Hammond (2001) subsequently utilised this formula to devise a similar expression for calculating the buoyancy-driven convective heat transfer in high-aspect-ratio cavities formed within advanced glazing systems.

The Churchill-Usagi interpolation formula (Churchill & Usagi, 1972) can also be used to yield a smooth transition between the two bounding or end states in the present case. Combining the asymptotic formulae for the *per capita* ecological footprint in 2003 and 2100 [equations 8-3 and 10-1 respectively], together with Churchill-Usagi interpolation formula, yields:

$$ef = GNI^{2/3} PD^{-1/10} \left[(0.0055)^{-P} + (K \cdot EI^m CR^n)^{-P} \right]^{-1/P} \quad 10-3$$

where $P = 6$ is typically found to yield a good fit over the transition region (Alamdari & Hammond, 1983; Churchill & Usagi, 1972; Hammond, 2001). This ensured that at the start of the century the correlating equation 8-3 applies, but over the 21st Century the energy intensity and carbon ratio changed to reflect low carbon energy strategies implicit in the SRES scenarios (equation 10-1). They therefore become progressively more influential as the century develops.

It was expected that energy intensity and carbon ratios would decrease in future worlds and therefore as that part of equation 10-3 decreases, the results would start to favour the new 2100 equation (equation 10-1) taking into account the changes in EI and CR. By updating the constant to 0.0055 in equation 8-3 (originally 0.0093 (Cranston *et al.*, 2010)) the transition to equation 10-1 is less immediate; hence the peak for the B1 developing world is a few years later than was initially postulated by Cranston & Hammond. (2010b).

10.3 SENSITIVITY ANALYSIS

A sensitivity analysis was performed to determine whether it was appropriate to use the SRES marker scenarios for the ecological footprint projections or whether these projections were significantly affected by the application of more recent population and economic data sets (see Chapter 5). The biggest criticism of the SRES scenarios was that the population trajectories were too high in some cases, and small updates were necessary for the projection of economic growth; this has been discussed in Chapter 5. However, for the analysis undertaken within this chapter it was considered necessary to verify and justify the use of the SRES marker scenarios by undertaking a sensitivity analysis. The potential total global ecological footprints from 1990-2100 were calculated using the population data from UN (Department of Economic and Social Affairs, 2004) and IIASA (Lutz *et al.*, 2001; Lutz *et al.*, 2007), and the economic growth data from Richels *et al.* (2004) and Weyant & de la Chesnaye (2006). These trends were then compared with the results for the total world ecological footprints produced for the four marker scenarios (Figure 10-6).

It was not possible to compare industrialised and developed regions here because the economic trajectories were only available for the world and could not be disaggregated. Despite this, these results can still be used to assess how relevant the SRES scenarios are in a global context, compared to the updated studies and how much they vary from new scenarios.

10.3.1 Selection of Scenarios

As has been discussed in Chapter 5, the IPCC scenarios from the SRES report were adopted throughout this thesis. This has been shown to be appropriate and the following analysis for the methodology and data selection corroborated and justified their use for this study.

The work undertaken throughout this chapter was based upon an updated correlating ecological footprint equation which required scenario data detailing affluence and population growth. The debate surrounding the economic trajectories and population projections within the SRES scenarios has been highlighted in Chapter 5 and it was necessary to further consider the relevance of the scenarios for this specific study. The four marker scenarios were assessed against a combination of high, medium and low

economic and population trends based upon UN data (Department of Economic and Social Affairs, 2004), IIASA (Lutz *et al.*, 2001; Lutz *et al.*, 2007), Riahi *et al.* (2007) and Weyant & de la Chesnaye (2006) to assess whether the SRES scenarios were acceptable in this study.

Energy intensity and carbon ratio have been shown to be important within the correlating equation for future scenarios (see section 10.2), and hence they were included in this analysis. The future estimates of energy use and carbon emissions from the IPCC have been shown to be acceptable (Chapter 5) and thus were employed from the SRES report. The value of energy use and carbon ratio varied according to the marker scenarios and their storylines. A range of energy intensities was developed from the different options of economic growth presented by Richels *et al.* (2004) (see Figure 10-5).

A matrix was set up to create estimates of future global footprints using the more recent data sets mentioned above and in Chapter 5. The structure of this matrix is explained in Figure 10-5.

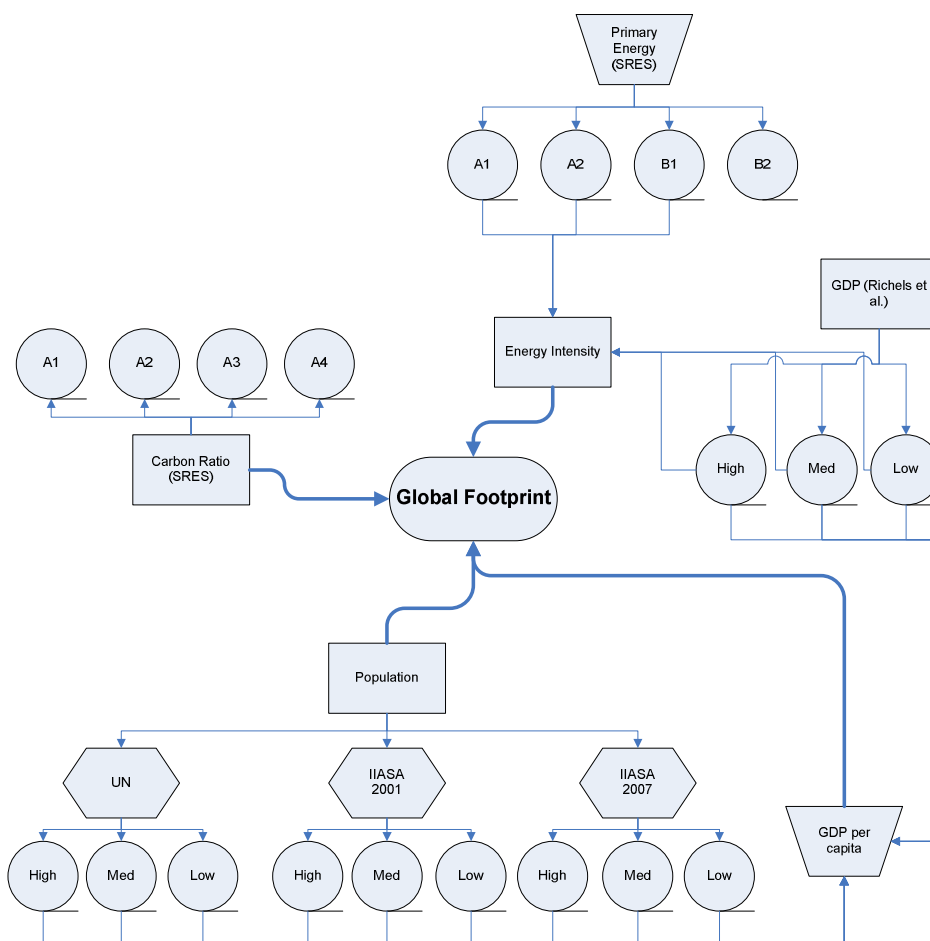


Figure 10-5: Flow diagram of updated data input to create future global footprint predictions

The data sets were applied to equation 10-3 with a detailed variety of combinations such that high to low population growth, slow and rapid economic transitions occurred and changes in technology and energy use were accounted for. A large range of future options was derived (Figure 10-6). These options do not have any storylines associated with them, but simply represent the combination of the updated data sets that were applied to equation 10-3. This analysis does not utilise any expert scenario formulation, but illustrates that even by utilising the updated population and economic growth trajectories the scenarios selected from the IPCC resulted in appropriate forecasts that fall within the range for possible future outcomes. The marker scenarios have undergone high levels of scrutiny, and without in-depth knowledge and models to formulate scenarios, it is not possible to create updated scenarios that would meet the extremely high requirements of the SRES.

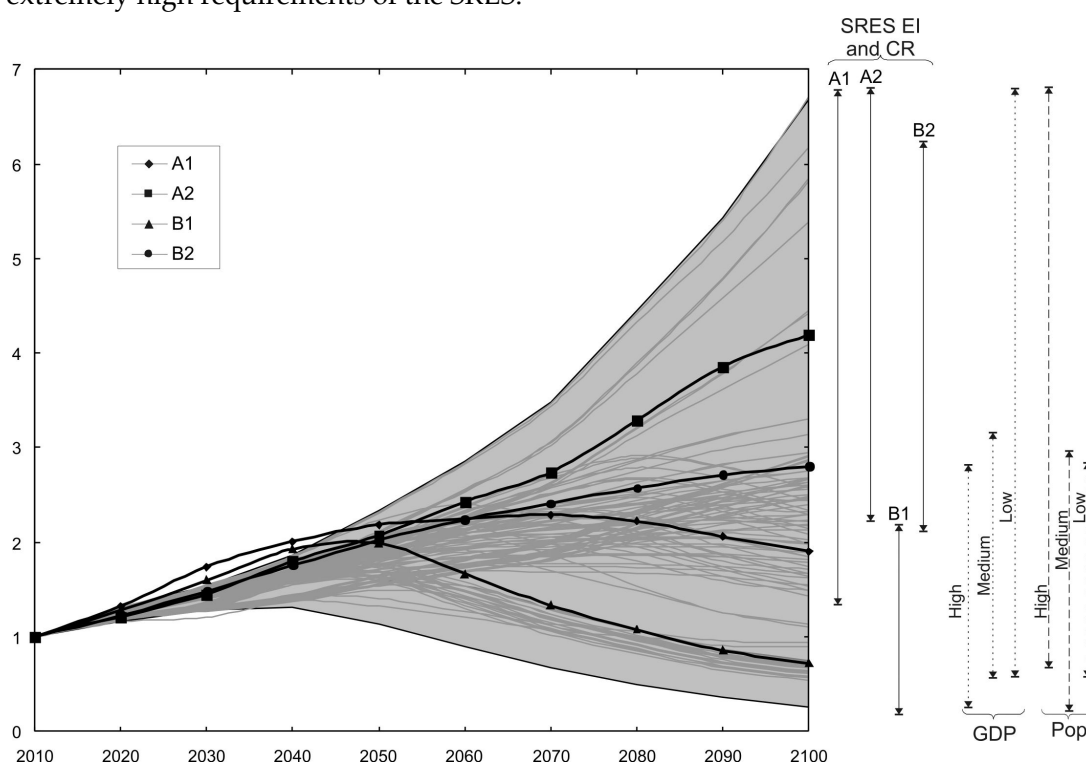


Figure 10-6: Range of scenarios possible from updated population and economic data sources

Data is normalised to 1 in 1990. Grey area represents range of alternative scenarios based upon UN (Department of Economic and Social Affairs, 2004), IIASA (Lutz *et al.*, 2001; Lutz *et al.*, 2007), Riahi *et al.* (2007) and Weyant & de la Chesnaye (2006). Grey lines represent the individual combinations.

It is the energy intensity and carbon ratio that become important in determining the footprint by the end of the 21st century, as can be seen by the variation in scenario options in Figure 10-6, with the variants using the B1 carbon ratio and energy intensity data having the lowest possible final footprint in 2100. It may appear counterintuitive for future worlds with lower affluence to have the higher total footprints, but this can be attributed to the lack of investments in new technologies, efficient methods and

improved resource use which in turn create a larger final footprint; this tends to coincide with high population growth.

Figure 10-6 shows that the B1 marker scenario follows the trend of a collection of the updated options, highlighting a low footprint pathway to the future, with a decreased final footprint in 2100. The A1 and B2 marker scenarios follow the swath of medium options in the middle of the range, whilst the A2 marker takes the upper level of the range, but there are still potential options above it.

It was important to select the appropriate scenarios for the research within this study. The sensitivity analysis highlighted the different options that could result from using more recent population and economic growth projections. It was concluded that the SRES four marker scenarios fall within the range of these possible futures, and were therefore considered appropriate to use in the analysis of future footprinting problems. The use of different population and economic welfare values does have the effect of altering the predictions for future footprints, but it was shown that the marker scenarios offer a suitable variety and represent the main trends created within the alternative forecasts.

10.4 INTERROGATING THE TRANSITION PATHWAYS

Having confirmed the use of the IPCC marker scenarios as appropriate forecasts in section 10.3 and determined the final future footprint expression to apply over the 21st century (section 10.2) it was possible to interrogate the different future worlds that may occur under each scenario, and compare the variations between the prosperous North and the majority South.

The projections of total ecological footprints (*per capita* footprint obtained from Equation 10-3 multiplied by regional population size) on a regional basis are presented in Figure 10-7. This plot has been updated to account for the change in constant to 0.0055 from 0.0093 to contrast with that initially stipulated by Cranston *et al.* (2010) due to a small error. This has the effect of reducing the starting footprint in 1990 to approximately 1400 gha and 3000 gha for the developing and industrialised countries respectively from that originally stated by Cranston & Hammond (2010b). Despite this reduction, the trends remain the same. The overall total footprint is smaller due to the lower constant that was established in the update of the correlating equation.

The future pathways for the developing and industrialised nations are quite different, and contrast depending on which of the four marker scenarios were implemented. Currently the industrialised countries maintain a larger total footprint than the developing world, although the two regions converge at approximately the year 2015 (see Figure 10-7). However, beyond this point these regions diverge, with the majority South accelerating towards much larger footprints than the North. The developed

world exhibits a much more gradual change in its ecological footprint; it reaches a maximum level of around 8.5 billion gha in 2100 and a minimum level of just over 1 billion gha for the A2 and B1 scenario storylines respectively.

The B1 scenario was expected to have the best improvements in terms of ecological footprint reduction due to the high priority for environmental development aimed at moving not only the industrialised but the whole world to a globally coherent and sustainable future. Through the implementation of the bounding equation 10-3, which combines equation 10-1 with the original equation 8-3 based upon the year 2003, the importance of improving energy usage and controlling the release of carbon emissions that is associated with the B1 scenario can be seen through the peaking and reducing trend for both the industrialised and industrialising regions of the world (Figure 10-7). The developing world has a rapidly increasing footprint up to approximately 2050, but this is eventually reduced significantly by the end of the century. The initial increases are attributed to the high level of economic activity at the start of the century, with only small improvements in energy intensity and carbon ratio. This is emphasised by the fact that the correlating equation for 2003 dominates at the start of the century and does not account for changes in emissions and improved efficiencies. However, once economies have grown sufficiently, any financial gains tend to be reinvested to advance environmental issues and protectionism, as can be seen in the latter part of the century for the developing world; the industrialised world shows a more immediate decrease in footprint as it is more economically advanced and has the technology and developments necessary to implement carbon savings, clean energy and sustainable living.

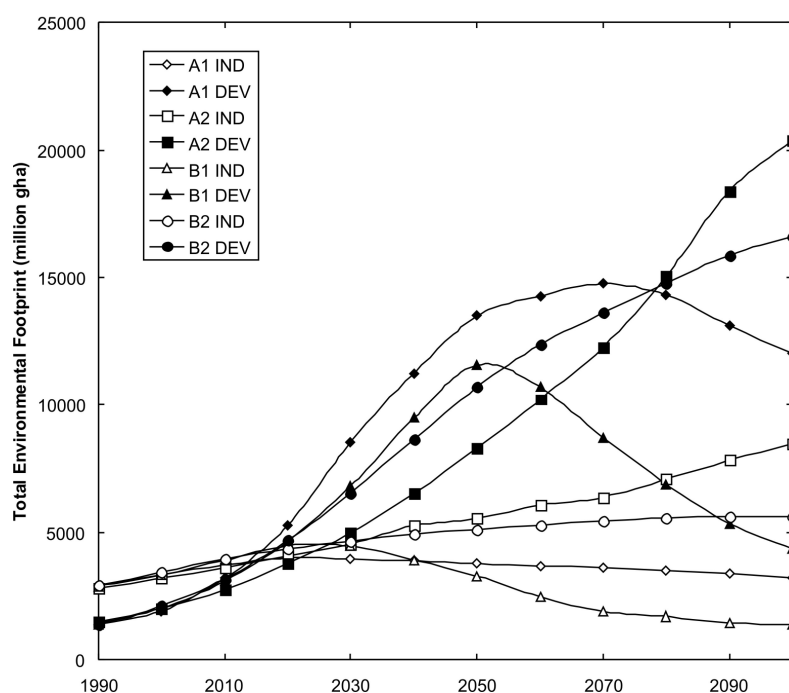


Figure 10-7: Regional Ecological footprints under the Marker Scenarios

The A2 scenario contrasts sharply with the results for the B1 marker, showing a continuously increasing footprint for both the majority South and the prosperous North with no indication of any contraction. The growth rate is slower for the developing world in this scenario when compared to other markers, but this can be explained by the nature of the storyline that it represents. The A2 family is characterised by a self reliance in terms of resources, development and growth, thus causing very little cross- and inter-regional interaction which results in minimal trade flows, slower technological advancement and hence a dampened acceleration in economic growth. Despite the relatively slow economic transition, the growth pattern continues throughout the century. With little interaction between regions, developments in technology tend to be advanced according to local resources, cultures and knowledge, resulting in unbalanced reductions in carbon emissions and small improvements in energy use. This family group is not orientated about environmental consciousness, but is focused upon supporting communities and preserving local identities. The combination of all of these factors causes the growth in ecological footprints for both the developing and developed world.

Figure 10-7 shows that the B2 and A1 scenarios follow the medium point between the two extremes of A2 and B1. Both show a plateau of total footprint values for the prosperous North throughout the second half of the century; although the A1 scenario represents a more immediate plateau earlier in the century at a lower constant level, caused by the sharing of ideas and globalisation within the storyline. Despite the B2 scenario having a focus upon sustainable development, the results shown here do not indicate a reduction in total footprint. There is an increased concern for environmental protectionism, but this is much slower to be implemented and is not equitable throughout the world since the B2 storyline represents few global interactions. The A1 scenario, however, does show some reduction in total footprint within the developing world by 2100. Predominantly caused by the rapid economic growth and implementation of advanced, efficient technologies globally that result in improved energy usage. This world is not driven by making environmentally conscious decisions, but instead technologies are utilised to maximise resources and manage Nature's capital.

Overall, the developing countries are responsible for approximately 75% of the worldwide ecological footprint by the end of the 21st Century, compared with only a 36% share at the turn of the Millennium. According to these scenarios the footprints for the industrialised and developing worlds seem unlikely to converge over this timescale; however, there is a tendency for the projections to converge sometime in the following century under the B1 scenario storyline. Here global population peaks by mid-21st Century, whilst the economy changes rapidly to a service and information economy resulting in lower material intensity. Global solutions are encouraged to ensure

economic, social and environmental sustainability via the use of cleaner and more efficient technologies.

10.4.1 *Per capita* Footprint Projections

The total ecological footprint for the North and South regions is shown in Figure 10-7; however the results are significantly altered when the analysis is considered on a *per capita* basis. Such *per capita* ecological footprints are considered for these regions in Figure 10-8.

The developing world has a far larger population than the industrialised world, and therefore the ecological footprint *per capita* will be smaller. The scenarios with large population growth, such as the A2 scenario, have lower *per capita* ecological footprints, particularly evident in the developing world. This masks the overall impacts of the total, far larger footprints that are associated with such high growth scenarios.

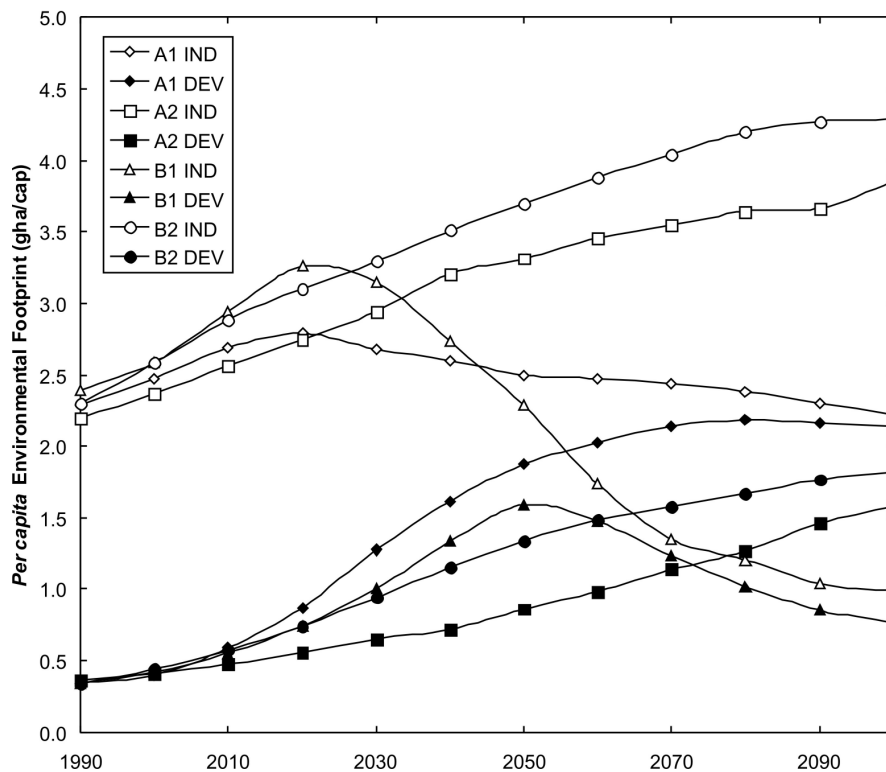


Figure 10-8: *Per capita* Ecological footprints for regions of the world up to 2100

The developing world is shown to have an increasing *per capita* footprint under all the marker scenarios except the B1 storyline (Figure 10-8). This B1 scenario sees high growth in *per capita* footprint up to the middle of the century caused by a growth in affluence, but there is a rapid drop to 0.77 gha/cap by 2100 as a result of the subsequent improvements in energy efficiencies, advanced technologies and a world striving towards sustainable development. This is matched by the results for the prosperous North, where following the B1 scenario the *per capita* footprint is reduced considerably

to 0.99 gha/cap by the end of the century. This shows not only a contraction but also a tendency towards convergence with the majority South at the start of the 22nd century in terms of *per capita* footprint usage. If these values can be achieved, assuming that biocapacity does not drop significantly, the globe may be able to climb out of overshoot, with every human being utilising a footprint below their allowance, enabling Nature's capital to replenish itself and be plentiful. The *per capita* footprint availability is dependent on population size, and the B1 world in 2100 does have a slightly higher global population than currently, 7 billion compared with 6.7 billion in 2008. The *Living Planet Report 2008* (WWF International, 2008) states that the global *per capita* footprint was 2.7 gha/cap in 2008, with a biocapacity of 2.1 gha/cap. If this biocapacity level can be maintained, with little degradation of land and improved productivity, the total amount of biocapacity available per person in 2100 for the B1 storyline will be 1.94 gha/cap. This is well above the value of less than 1 gha/cap for the developing and developed worlds suggested for the B1 scenario by the end of the century, thus enabling humanity to move away from overshoot and maintain a healthy balance with Nature's resources and stocks.

The A1 world implies a convergence between the developing and industrialising worlds at just above 2 gha/cap – not low enough to achieve a move out of overshoot. This is still a high *per capita* value and the developing world shows no reduction until the last couple of decades in the 21st century. However, it is encouraging that there is some apparent equity between the prosperous North and majority South, as they move towards a similar *per capita* ecological footprint. This convergence between the two regions of the world for both the A1 and B1 scenarios is due to the globalisation, urbanisation and sharing of ideas throughout the world, causing international growth and collaboration between the developing and industrialised regions. In contrast there is some disparity between the two regions for the A2 and B2 scenarios, with no indication of convergence, but simply a continuation of growth in all paths. This type of growth is not sustainable, and with increasing global populations it will require a resource capital far above that which the planet can provide each year. The available natural capital stock will eventually deplete if this demand continues to increase, since Nature cannot replenish itself fast enough.

10.4.2 Future Global Footprint Trends

The situation in regard to the worldwide ecological footprint is illustrated in Figure 10-9. This depicts the total global ecological footprint projected for a combination of both the developing and industrialised regions. The general trend is that the A1 and B1 scenario storylines suggest the possibility of a diminishing total ecological footprint from approximately 2050 onwards. This is driven by the desire for environmental improvements within the B1 storyline which causes energy intensity levels to reduce, implements careful resource use and brings about a desire and move toward sustainable development through global strategies. The A1 situation does not strive towards environmental protectionism but instead is driven by the growth and

internationalisation of economies, which often results in improvements in technologies that impact energy efficiencies, resource use and subsequent emissions. The two remaining storylines, A2 and B2, are heavily biased towards local solutions and take pride in maintaining regional identities. The B2 marker scenario has a tendency towards environmental issues, thus having a lower total footprint than the A2 world, however without the sharing of ideas, trade and markets it is difficult for the entire globe to benefit from any regionally innovative improvements.

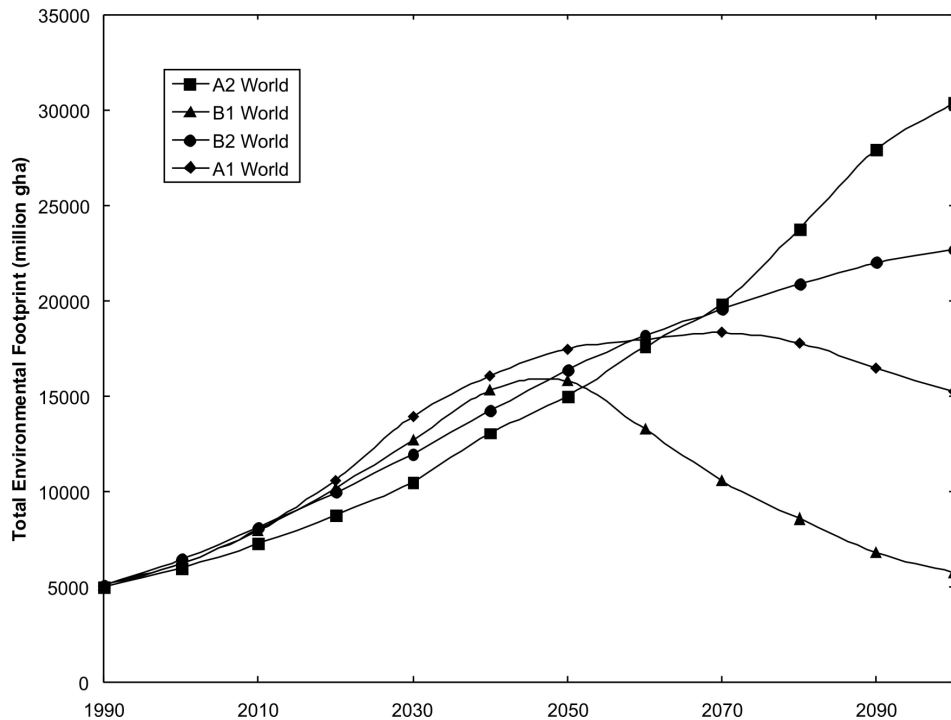


Figure 10-9: Global Ecological footprint under the Marker Scenarios

10.5 LIMITATIONS

There are a variety of limitations associated with the analysis undertaken in predicting future ecological footprints up to the end of the 21st century as presented here. This is purely a mathematically and theoretical model, and as such does not account for any changes in the fundamental sectors within the footprint makeup, for instance there will likely be continued degradation of land and the transformation of land type such as forests to agriculture or built land requirements as the population grows and urbanises. The footprint is essentially a land based unit, so any changes in land use and over use or degrading of land should ideally be included. Such changes are dynamic and dependent upon many other factors and unknowns. The problem of cumulative carbon dioxide is also not analysed, nor is its subsequent effects upon the atmosphere. Carbon dioxide has serious impacts upon climate change through augmenting global temperatures, melting ice caps and rising sea levels. These problems will have serious effects upon the shape of the future footprints, but with so many uncertainties it is difficult to assess how best to include them within footprinting models.

There are of course many other overarching problems, including water resources, malnutrition, illness and the spread of disease. Again it is hard to quantify these issues in terms of footprint results. The footprint's limitations have been discussed (Chapter 3); one of the key arguments is that it should be used as one in a tool kit of indicators. Another appropriate indicator is the Human Development Indicator (HDI). This statistic is useful to demonstrate differences between nations in terms of their life expectancy, education, GDP and standard of living, offering a very different picture to that presented by the footprint, and therefore considering the social aspect of the 'Three Pillars' (UN, 2002). It is demonstrated in Figure 10-10 that countries with a higher level of HDI tend to have a higher footprint; the industrialised countries are located in the top region of both plots. However, it is significant to note that whilst the industrialised countries have considerably increased their footprints, they have not dramatically improved their HDI levels. There is a large range of footprint sizes even within the developed world, but this is not reflected in an array of HDI levels (Figure 10-10). Overall the footprint levels in the prosperous North are high and there is little correlation with the magnitude of improved HDI as the footprint size increases.

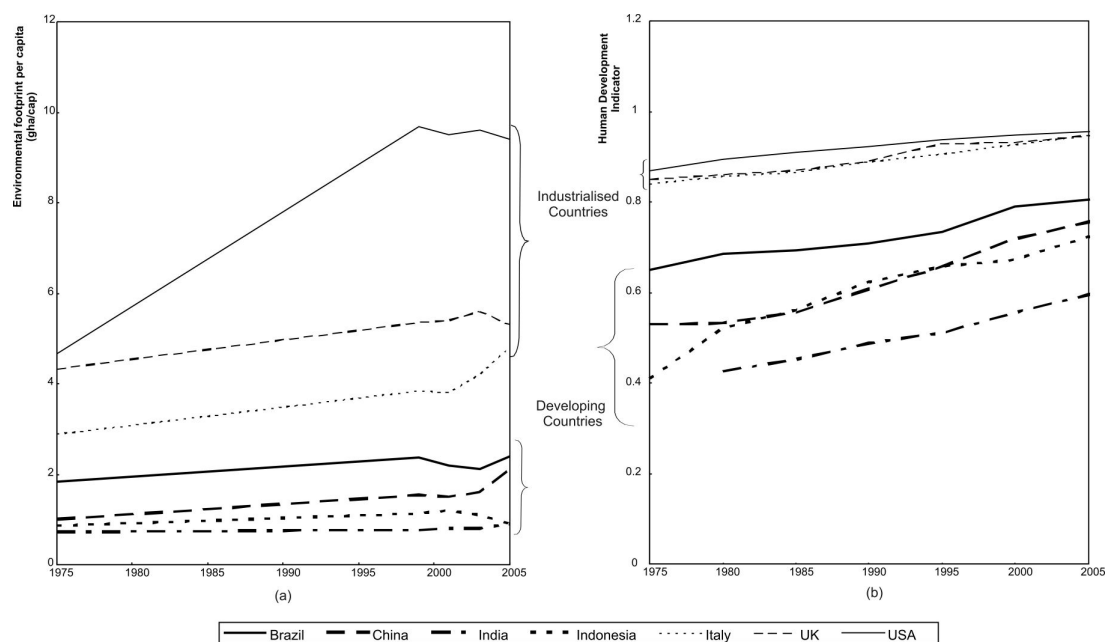


Figure 10-10: Comparison of (a) *per capita* ecological footprint and (b) HDI for a selection of nation states in the developing and industrialised world

Data sourced from Global Footprint Network (2006b), WWF International (2002, 2004, 2006, 2008) and UNDP (2009a)

Many people within the North have far higher living standards and greater expectations of life quality than the peoples of the South. The footprint values contrast between the North and the South, with the developing countries maintaining relatively low *per capita* ecological footprints but showing large development in terms of their HDI. Indonesia has even had a small decrease in footprint, but continued to increase its

HDI score. The spread in footprint values for the developing nations is reflected in the range of HDI levels for these countries. This suggests that reductions in large footprints would not impact heavily upon HDI levels of many nation states; there may be an effect upon the perceived lifestyles particularly in the affluent North, but for the majority South this will be minimal. There needs to be a far better balance, understanding and equity between these two major regions of the world.

Including all of the issues above is out of the scope of the research remit in this case, but it is important to consider the restrictions, limitations and problems with this type of systematic and theoretical analysis. By critiquing the results there can be a better understanding of future problems. It may be that these results are actually under estimates, given that they do not account for such dramatic changes as described above. This implies that future disasters may occur, and the onset of contraction and convergence may not be as pronounced as has been suggested for some future worlds, as shown by the B1 storyline.

10.6 SUMMARY

This chapter considers the development of the footprint into the future. Through the use of IPCC marker scenarios and the correlating equations adapted from Chapter 8, four different pathways into the future are discussed. The prosperous North and populous South are compared and contrasted up to the year 2100. This work is novel since it builds upon the work and subsequent equations developed in Chapter 8. Future footprint scenarios have not been built up in this manner before, but instead depend upon a host of assumptions, looking primarily at 'deep green' or 'business as usual' forecasts. This work is motivated by the use of a correlating equation that relates important determinants to the footprint and can be adapted for situations looking beyond present day. It is shown that as the majority South develops, the associated footprint rapidly overtakes that of the affluent North. The scenarios range in characteristics, some offering positive reductions and potential contraction and convergence trends into the next century, whilst others are far more pessimistic, offering very little interregional or international collaboration with minimal interest in lowering consumption trends, resulting in extremely high footprint values.

Aim 2 is met in the chapter, as the differences between the developing and industrialised regions of the world are compared with particular focus upon future pathways. This is achieved through Objective 6, which enables the adoption of scenarios and development of the correlating equation to identify alternative footprint futures for these contrasting worlds.

CHAPTER 11

CONTRASTING CARBON CONTRIBUTIONS

11.1 INTRODUCTION

The consumptive world in which humans live has led to an increase in anthropogenic emissions, particularly carbon dioxide (CO₂) – the main ‘greenhouse gas’. It has been widely accepted amongst the scientific community that the growth in average global temperatures is very likely to result from the increasing anthropogenic greenhouse gas (GHG) concentrations (IPCC, 2007a), principally associated with the burning of fossil fuels. In 2005, carbon dioxide concentrations in the atmosphere were recorded to be 35% higher than 150 years earlier, with the majority of this rise occurring since 1995. These rising CO₂ levels are degrading the environment and damaging global ecosystems.

Global anthropogenic emissions have risen considerably over the last century (Figure 11-1), and are predicated to continue to grow into the next century. The overall trend has shown continuous growth in global emissions, although some small downturns can be noted in the 1970s due to the oil crisis, 1980s caused by the recession early in the decade and in the 1990s as the Soviet Union was split up and its subsequent economic problems. The current economic crisis (IMF, 2009) may well cause such a downturn as well. Historically the industrialised world had a far larger share of the global carbon emissions than the developing regions (Figure 11-1), with rapid industrialisation starting during the Industrial Revolution and continuing into the 20th century and beyond. In more recent times the developing countries have been catching up with industrialisation processes and in turn producing more and more emissions, such that they almost have an equal share with the industrialised countries (Figure 11-1). Indeed, for Asia alone, the carbon emissions more than doubled between 1990 and 2006 (IEA, 2008).

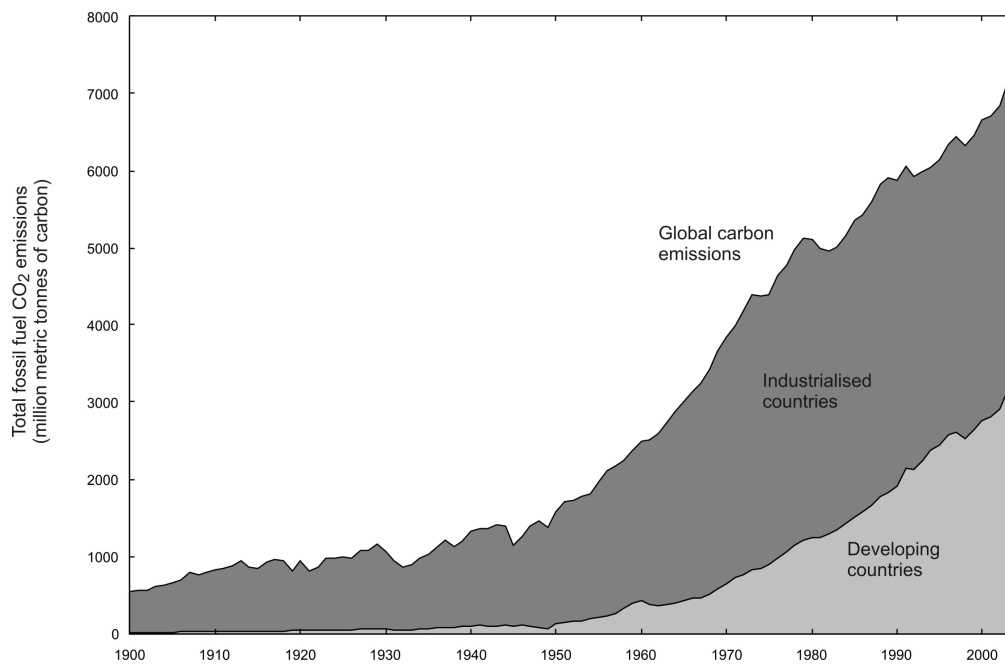


Figure 11-1: Global fossil fuel carbon emissions and the share of industrialised and developing countries

Today the concentration levels of CO₂ are far higher than 100 years ago, and are dominated by those emitted from the industrialised countries of the North. However, developing countries have progressively increased their contribution to global emission levels. In fact, the year 2004 saw the industrialised world being responsible for 54% of global fossil fuel carbon emissions, with the developing world holding a 46% share. The split in the emissions share is therefore no longer dominated by the developed North, but has changed over the years as the majority South develops and grows. This has been predicted to continue to change as we head further into the 21st century. The increase in atmospheric concentrations is often attributed to two factors: population growth and economic development. The affluent North have huge economic advantages, but some of the largest developing economies of the majority South, where 80% of humanity live, are growing rapidly in terms of both population and economic wealth. The sustainability (or IPAT) equation has been employed in this chapter to assess the relative contribution of population and economic growth to carbon emissions as the two contrasting regions of the world develop into the future.

This chapter uses manipulations of the IPAT equation to assess the key contributors to growing carbon emissions within the developing and industrialised worlds. This work therefore achieves objective 7 and contributes to Aim 2 by comparing and contrasting these two different worlds in terms of their carbon consumption.

11.2 CARBON QUOTAS

The 'energy land' category of the ecological footprints (see Chapter 3) reflects the area required for new forests (anywhere in the world) needed to absorb carbon dioxide, and

thereby stabilise the atmosphere. It has been suggested that this influential, often dominant, land type could alternatively be calculated, for example, from the area required to replace fossil fuels with wood biomass (Chambers *et al.*, 2000) (see also section 3.7.2.1, pp.29. Per capita carbon emissions are closely associated with economic wealth, and hence with the United Nations Development Programme (UNDP) ranking according to their Human Development Index (HDI). Industrialised countries, particularly the USA, emit a large fraction of total greenhouse gases (see the corresponding annual total CO₂ emissions for 2003 shown in Figure 11-2), and might be required to significantly curtail their carbon emissions in any future climate change mitigation regime that might succeed the Kyoto Protocol. The UK Government, for example, has committed itself to reducing CO₂ emissions by 80% by 2050 against a 1990 baseline (Cranston *et al.*, 2010). In that timeline, many of the other environmental effects that contribute to global and national footprints will have come to the fore. On the transitional pathway towards a low carbon future in 2050, CO₂ quotas for the developed countries would need to fall, while those of poorer developing nations would perhaps be permitted to rise with economic wealth and (hopefully) well-being (see Chapter 10 for future scenarios); thereby removing 'grandparent emissions' (cumulative or historic national emissions).

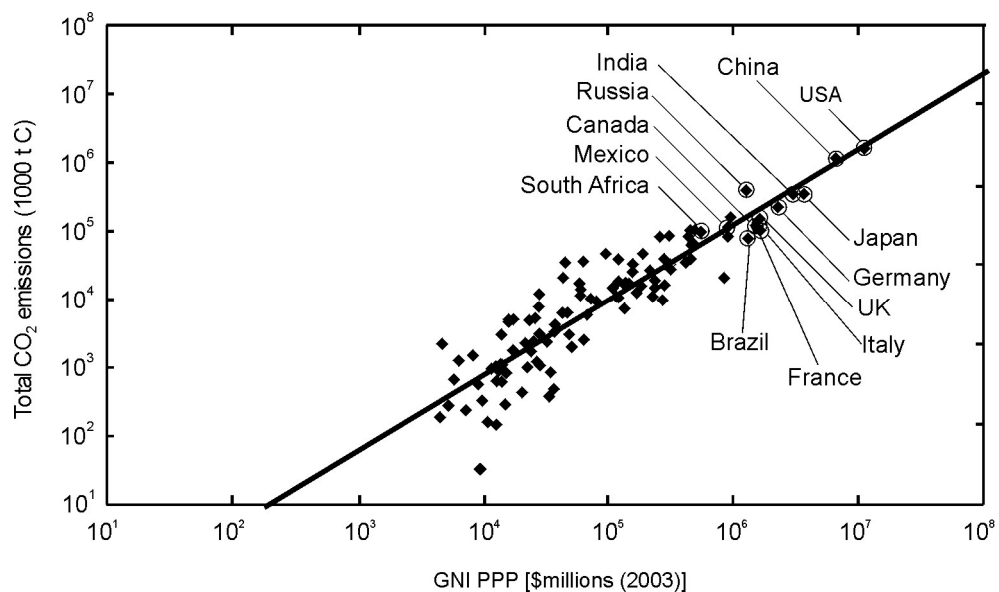


Figure 11-2: Total annual carbon dioxide emissions for nations around the world

There are ongoing negotiations within the ambit of the UN Framework Convention on Climate Change (UNFCCC) over the successor regime to the Kyoto Protocol. The major players have indicated what they might contribute to CO₂ mitigation in the medium term. The European Union, which emitted 4,721 Mt of CO₂ in 2006 (10.22 t per person (US EIA, 2009)), formally negotiates on behalf of its members. It has suggested that it will cut emissions by 20% on 1990 levels by 2020, although with the possibility of increasing this target to 30% should a new climate deal be agreed internationally. The USA is the largest emitter of carbon worldwide (see Figure 11-2): 5,903 Mt of CO₂ in

2006 (19.78 t per person). However, the Obama Administration has only committed itself (subject to the approval of Congress) to return its emissions to 1990 levels by 2020 (Cranston *et al.*, 2010). The Russian Federation emitted 1,704 Mt of CO₂ (12.00 t per person), and has set an emissions target of a 10-15% cut by 2020 compared to 1990 levels. The new Japanese Prime Minister Yukio Hatoyama announced a 25% cut in GHG emissions by 2020 on 1990 levels in September 2009. Japan emitted 1,247 Mt of CO₂ in 2006 (9.78 t per person). The PRC (People's Republic of China) emitted 6,018 Mt of CO₂ in 2006 (4.58 t per person). China will not reduce overall annual emissions, but is committed to establishing a 'carbon intensity' target. They have also pledged to use 15% of renewable energy sources by 2020, and plant 40 million hectares of new forest as a carbon sequestration measure (Cranston *et al.*, 2010). India, which emitted 1,293 Mt of CO₂ in 2006 (1.16 t per person), has indicated that it will resist any attempts to impose binding caps on it. Their government believes that the industrialised countries should take responsibility for carbon mitigation. Nevertheless, India has suggested that it might take 'aggressive' voluntary action to combat climate change (Cranston *et al.*, 2010).

Carbon dioxide released into the atmosphere from the burning of fossil fuels is thought to persist for (or have a residence time of) around a hundred years. The build-up of atmospheric CO₂ concentrations is therefore largely a consequence of emissions released by the countries of the North since the start of their so-called 'industrial revolution' around the turn of the 18th Century. Thus, the USA has emitted about 314,772 Mt of CO₂ over the period 1900-2004 (US EIA, 2009). Historic emissions from the EU during the same timescale amounted to 273,221 Mt, while that of Russia and Japan totalled 89,688 Mt and 42,696 Mt respectively. This can be contrasted with the cumulative emissions from China and India of 89,243 Mt and 25,054 Mt respectively. It can consequently be argued, on equity grounds, that the industrialised nations should take the lead in mitigating the global release of GHGs, because they are principally responsible for their life-time concentrations.

11.3 CONTENTION REGARDING CUMULATIVE CARBON

Since the start of the 20th century, CO₂ emissions from the industrialised world have been significant and accumulating over time as this region of the world underwent industrial revolution. Thus, although the developing regions are rushing to industrialisation, the world is still suffering from the effects of the prosperous North's own industrial expansion. Indeed, Figure 11-3 demonstrates that in terms of cumulative carbon, the majority South will not reach the same levels as the North until approximately the middle of the 21st century, despite their total emissions each year being predicted to rise well above the North's decades before this. This highlights the need for the industrialised North to lead the way with clean technology and developments towards environmental protectionism and to encourage the South to adopt such practices.

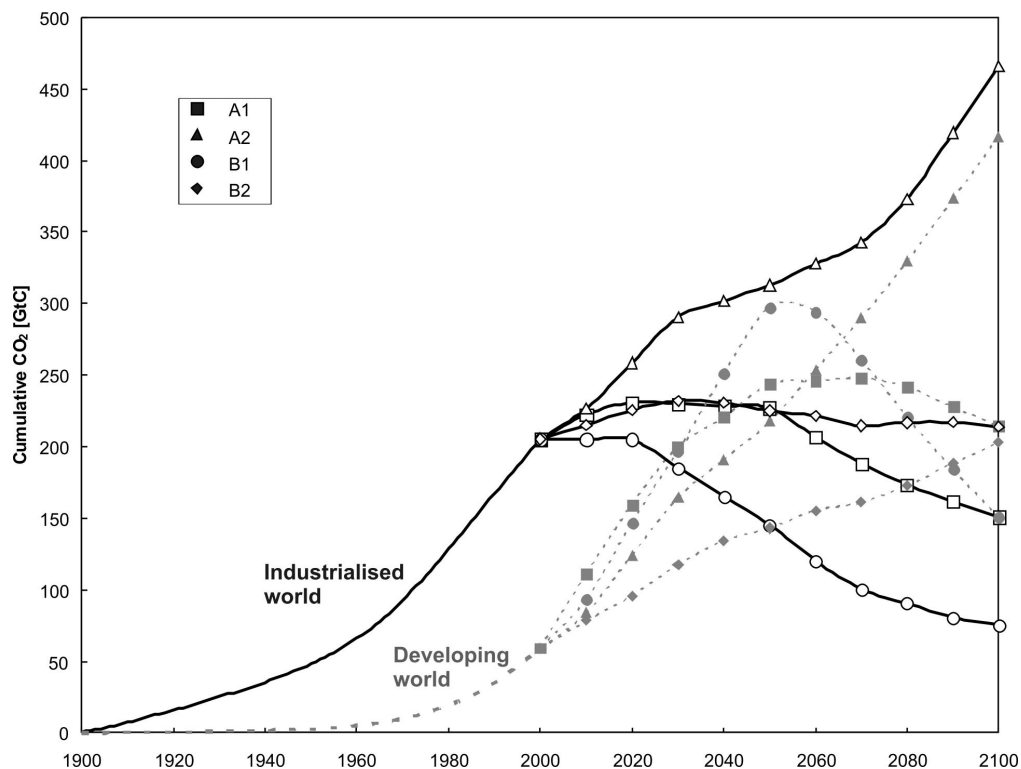


Figure 11-3: Historical and Future Cumulative Carbon for Industrialised and Developing World

The interaction between economic growth and environmental activity has long been discussed and debated (Shafik, 1994). Opinion is split in terms of whether the effects of increasing affluence will be positive or detrimental. Many believe that by increasing economic activity there will eventually be an environmental collapse and serious degradations, whilst others follow the belief that through economic growth humanity will be able to solve any ecological problems. It is generally accepted that growth in affluence has both negative and positive attributes. The developed world, particularly the OECD, have a high level of economic interdependence and integration. Being wealthy countries they can advance technologically and engage in innovative conservation in terms of resource use and utilise substitution methods when faced with fuel shortages or environmental dilemmas. It has been argued that although growth in economies may not positively benefit emissions, a level of technological development resulting from income allows countries to adapt to external shocks and unforeseen circumstances (Moomaw & Unruh, 1997).

It is considered that population and economic growth are not necessarily linearly related or proportional (Dietz & Rosa, 1997). Dietz & Rosa (1997) discuss the impacts of population and affluence upon emissions and conclude that both can be considered as driving forces. An increase in economic growth tends to increase the emission of carbon

dioxide; although reductions were noticed for the wealthiest countries which have shifted to a service-based economy and have invested in energy efficiencies.

The objective of the work presented in this chapter was to determine whether it is population or economic wealth that contributes most significantly to overall carbon emissions. The concept of economic or population growth effecting CO₂ emissions is not new, however, Raupach *et al.* (2007) stated that “a long-term (multidecadal) perspective on emissions is essential because of the long atmospheric residence time of CO₂”. This study undertakes this challenge, by analysing not only the historic emissions, but also future changes, thus spanning a 200 year period. This was necessary to highlight the changes that have occurred and the developments that may take place in the future. There have been no studies that utilise such a long timescale, for example Raupach *et al.* (2007) focus upon 1980-2005 and Gurer & Ban (1997) look only at the period 1970-1994. By undertaking a large timescale the trends and patterns across these different regions were assessed carefully and considered once again with respect to the IPCC marker scenarios. Thus it was possible to indicate the relative magnitude of the impacts that are likely to be caused by the wealthy North or the developing South over the coming century.

The impacts of population growth and economic wealth were assessed using the so-called IPAT equation (described below), together with an evaluation of past and future trends. Historic data was employed to determine past performance, while four different ‘marker’ scenarios produced by the IPCC in its *Special Report on Emissions Scenarios* (Nakicenovic *et al.*, 2000) (see Chapter 5 for details) were used to study likely trends up to the year 2100.

11.4 THE SUSTAINABILITY OR ‘IPAT’ EQUATION

The generic links between environmental burdens or impacts (I) flowing from a population of a given size (P), its economic wealth or affluence (A), and the extent and efficiency with which it uses resources and technology (T) were encapsulated in a simple equation $[I = PAT]$ devised by Ehrlich & Holdren (1971) (see also Chapter 6).

The IPAT equation was developed to emphasise the effects of population size and growth upon environmental degradation. This was further considered by Commoner (1972) who believed that technology was the key factor in causing environmental damage to the ecosphere. This opinion is slightly outdated now, especially given the huge improvements in transforming technologies that make significant changes in CO₂ emissions and resource degradation. The IPAT equation has frequently been used to investigate energy intensities, population growth and changes in affluence (Gurer & Ban, 1997). Indeed York *et al.* (2003) identify the IPAT equation as readily understandable and helpful in illustrating the effects of population and economic development upon environmental issues.

The IPAT equation is adopted in here and the debate surrounding the influential impacts of the four key driving forces are discussed in conjunction with development within the majority South nations and the prosperous North. Affluence, or economic consumption by an average individual, is traditionally measured by economists using the concept of the Gross Domestic Product (GDP) *per capita*. In the period since the early 1960s this has tended to increase over time in the wealthy countries of the Western industrialised world, whilst typically falling in the poorer nations of the majority South. The situation with demographic growth has been quite different to these booming economies with almost stable population levels in numerous affluent countries of Northern Europe. In contrast, rapid population growth has been observed in many parts of the developing world: Africa, continental Asia, and Central and South America. The 'technology' component in the IPAT equation represents the environmental damage per unit of consumption. In order to determine CO₂ or other pollutant emissions, an extension known as the Kaya identity is often employed (Kaya, 1990) (equation 11-1).

$$\text{CO}_2 = \text{Population} \times \frac{\text{Economic Wealth}}{\text{Population}} \times \frac{\text{Energy Use}}{\text{Economic Wealth}} \times \frac{\text{CO}_2}{\text{Energy Use}}$$

$$C = P \times G \times EI \times CR \quad 11-1a$$

$$C = P \times G \times F \quad 11-1b$$

$$\begin{aligned} \text{where, } F &= \frac{\text{CO}_2}{\text{GDP}} = \frac{\text{CO}_2}{\text{Energy Use}} \times \frac{\text{Energy Use}}{\text{GDP}} \\ &= EI \times CR \end{aligned}$$

C represents the carbon emissions (GtC), P is population (million), G is *per capita* GDP (\$; market exchange rate), EI is energy intensity (MJ/\$) and CR is carbon ratio (µg C/J). Waggoner & Ausabel (2002) refer to Equation 11-1a by the acronym ImPACT.

It has been noted by York *et al.* (2003) that the determinants of carbon emissions are inextricably linked, such that each variable does not influence the emissions independently. Thus, in order to understand the relative significance of each parameter, their potential rate of change has to be assessed. This multiplicative form of the Kaya identity can be manipulated such that the growth rates are additive (Gurer & Ban, 1997; Nakicenovic *et al.*, 2000). For example, carbon dioxide emissions from the mid-nineteenth century have grown by approximately 1.7% per year (Nakicenovic, 2000; Nakicenovic *et al.*, 2000). This can be broken down into the individual factors, such as:

$$\begin{aligned} 1.7\% = & 1\% \text{ population increase} \\ & + 2\% \text{ growth in } \textit{per capita} \text{ income} \\ & + 1\% \text{ decline energy intensity of world GDP} \\ & + 0.3\% \text{ decline in carbon intensity of primary energy.} \end{aligned}$$

This has been described mathematically by Gurer & Ban (1997) taking the assumption of continuous changes in each parameter of the Kaya identity and manipulating the equation using logarithms and subsequent differentiation (equation 11-2).

$$\frac{dC}{C} = \frac{dP}{P} + \frac{dG}{G} + \frac{dEI}{EI} + \frac{dCR}{CR} \quad 11-2$$

In a similar manner, Raupach *et al.* (2007) defined the proportional growth rate of a quantity $X(t)$ as $r(X) = X^{-1} dX/dt$ (with units $[\text{time}]^{-1}$), the counterpart of the Kaya identity for proportional growth rates is shown in equation 11-3.

$$r(C) = r(P) + r(G) + r(EI) + r(CR) \quad 11-3$$

The global emission C can be expressed by summation of the above factors. Through this analysis it is possible to determine which parameters contribute most to the growth in carbon dioxide emissions. The mathematical manipulation is shown in Figure 11-4.

Taking the Kaya identity:

$$C = P \times G \times F \quad 11-1b$$

$\log C = \log P + \log G + \log F$

Differentiating with respect to time:

$$\frac{1}{C} \frac{dC}{dt} = \frac{1}{P} \frac{dP}{dt} + \frac{1}{G} \frac{dG}{dt} + \frac{1}{F} \frac{dF}{dt}$$
$$\frac{dC}{C} = \frac{dP}{P} + \frac{dG}{G} + \frac{dF}{F} \quad 11-4$$

Figure 11-4: Mathematical manipulation of carbon contributing factors in the Kaya equation

The growth rates analysed in this chapter were evaluated from a base year of 1990 and added cumulatively to the end of the century. This was achieved via a decomposition of the terms in the IPAT expression (equation 11-1b). They were assessed to establish which variables gave the most significant contribution to the growth of carbon emissions over the twenty-first century. Both historical data and the IPCC marker scenarios (Nakicenovic *et al.*, 2000) for the developing and industrialised world were employed. In order to understand the effects of population growth and economic prosperity upon the emissions of carbon dioxide, a large time scale of 200 years was adopted.

11.4.1 Historical Data

A variety of sources were employed to represent historical data. Carbon trends were established from regional data for the developing and industrialised world from the CDIAC (Carbon Dioxide Information Analysis Center) databases (Marland *et al.*, 2008). Total fossil-fuel emissions were adopted in order to include emissions from gas, liquid and solid fuels, as well as emissions from gas flaring and cement production where appropriate. Emission estimates were expressed in metric tonnes of carbon.

Population data for the early 20th century was taken from two publications (National Academy of Sciences, 1971; UNDP, 1953). These statistics only dated as far as 1950. Data post 1950 was utilised from the UN (Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat, 2009).

Economic wealth was measured in terms of 1990 International Geary-Khamis dollars, an indicator similar to Purchasing Power Parity (PPP). *Per capita* economic wealth trends were assumed from Maddison's comprehensive database (Maddison, 2009). This detailed database was verified with his most recent book (Maddison, 2006).

There were no readily available energy data from 1900. However, it was possible to find the Carbon Intensity (CO_2/GDP) [F] value that is the combination of energy intensity and carbon ratio by using the Kaya identity since each factor is summed to give the change in carbon emissions.

11.4.2 Future Data

The IPCC's *Special Report on Emission Scenarios* was utilised for four marker scenario predictions up to the year 2100 (as discussed in Chapter 5). The population growth within the industrialised world was very similar for all four markers, with the total population size remaining almost constant. This contrasts sharply with the developing countries where, in both the A1 and B1 scenarios, the population peaks and then begins to fall around the year 2050. The A2 and B2 scenarios assume a continuous population growth, with the A2 scenario incorporating a large 'boom' in the number of people in the developing world.

Economically, the developing world has been growing faster than the industrialised countries over recent decades, but each of the marker scenarios reflect different rates. Thus, A1 implies a huge rise in economic wealth, whereas A2 is far more modest. The industrialised regions follow a more moderate growth pattern under each scenario, but with the A1 scenario having a significantly larger final economic wealth than the other scenarios.

These marker scenarios offered continuity from the historic data collected for carbon emissions and population growth. The problem arose with GDP as the historical data was measured in a PPP equivalent whilst the IPCC use Market Exchange Rates (MEX). This was not an issue when looking at percentage change or growth as these are dimensionless, and it was proven that both indicators were appropriate and could be used interchangeably when applied in this manner. A debate has surrounded the way in which the income projections adopted by the IPCC were expressed in terms of *Market Exchange Rates* (MEX), rather than *Purchasing Power Parity* (PPP). The IPCC's working group (IPCC, 2003) considered that over long time periods the rates of economic growth in terms of MEX and PPP tend to converge for less developed regions. Studies have shown that the choice of exchange rate for GDP does not greatly affect the projected GHG emissions if used consistently (IPCC, 2007a; IPCC, 2007b). Indeed, despite being one of the most hotly debated aspects surrounding the SRES scenarios, the economic growth trends do not vary significantly (IPCC, 2007a).

11.5 DEVELOPED AND DEVELOPING REGIONS OF THE WORLD

Scenarios were separated into the developing and industrialised worlds (see Chapter 7), so that the wealthy North could be compared with the poorer, but more populous, South. The ways in which population size and economic wealth growth differs quite significantly between these two regions. Data was taken from the IPCC *Special Report on Emissions Scenarios* with the industrialised North encompassing the OECD-90 (North America, Western Europe and Pacific OECD) and countries undergoing economic reform (Central and Eastern Europe and the newly independent states of the former Soviet Union). The developing South represented the rest of the world in Asia, Africa and Latin America.

Much of the data collected was regional data, and had to be adjusted and summed to give the totals for the majority South (developing world) and the prosperous North (industrialised world). The breakdown is shown in Table 11-1.

Developing South	Industrialised North
Africa	Centrally Planned Europe (Eastern Europe)
Central America, South America, and the Caribbean Nations	North America
Centrally Planned Asia	Western Europe
Far East	Australia, Japan and New Zealand
Middle East	
Oceania (minus Australia, Japan and New Zealand)	

Table 11-1: Breakdown of nations States in the Developing South and Industrialised North

11.6 DETERMINING THE MOST SIGNIFICANT DRIVER

11.6.1 The Approach

The rise in CO₂ emissions can be attributed to increasing worldwide economic prosperity and an expanding global population. The significance of these two factors in effecting carbon emissions was postulated to vary between the developing and industrialised world. The IPAT formula (equation 11-1a) was utilised to determine which of these parameters is the principal determinant of CO₂ emissions. The rate of change in the trajectory of each determinant was evaluated, using both historical data and future scenarios (equation 11-4). A similar approach was recently adopted by Raupach *et al.* (2007), who studied the drivers of carbon emissions both globally and in a number of sub-regional groups. This can be simplified as demonstrated in equation 11-4, and equation 11-5 shows an example for population growth from the base year 1990 to the following decade.

$$\text{Cumulative \% population growth} = \left(\frac{P_x - P_{n+10}}{P_{n+10}} \right) + \left(\frac{P_{n+10} - P_n}{P_n} \right) \quad 11-5$$

where n = base year, 1990

x = decade under analysis

These datasets were manipulated to determine the various parameters in the IPAT equation: energy intensity [EI] (MJ/\$), carbon ratio [CR] (μgC/J) and GDP/capita [G] and subsequently carbon intensity [F] (gC/\$). The base year of 1990 was chosen and all data was normalised around this date. The growth, or change, in each factor is relative to this base year. The gradient of each line represents the relative growth or decline of that determinant. For example, the trends for economic wealth historically and in the A1 scenario show a growth in economic prosperity for both the industrialised and developing world (Figure 11-6).

11.6.2 Contrasting the Developing and Industrialised Worlds

The developing world has a far greater share of the global population, at approximately 80%. The bulk of the population in developing countries reside in rural areas. However, in the rapidly emerging nations, such as China and India, the work force is being urbanised as they adopt more advanced technologies in a bid to become industrialised. If this transition towards industrialisation is undertaken in a 'sustainable' way (by, for example, making use of best practice, low carbon technologies secured from the developed world), it may be possible for the developing world to maintain a lower *per capita* carbon footprint than the prosperous North (where only some 20% of humanity resides). It would appear that fast learners have a distinct advantage, since implementing something already invented is far easier than designing and developing it from scratch. This may help to explain how the emerging economies of, for example India and China, are able to gain so much ground on the leading economies (Commission on Growth and Development, 2008). The growth rates for developing economies are higher than those already at the forefront of technological changes, as they rapidly approach industrialised levels of material consumption. These high-growth economies are able to converge with leading economies as they have such a large work force. Much of the developing world's large population is unemployed or underemployed, and therefore would welcome an opportunity for more productive work in the cities. This represents a move not only to industrialisation, but also to urbanisation (Commission on Growth and Development, 2008). During this high growth, industrialisation phase of development in the South, there will be an inevitable increase in the per capita CO₂ emissions. However, it may be possible to avoid carbon emissions rapidly increasing by encouraging the adoption of mitigation measures to limit GHG emissions. Otherwise it will be necessary to adapt to climate change, perhaps on a grand scale. Developing countries need to grow, but coupled mitigation measures are often too expensive and low down on their agenda.

It has been suggested that in developing countries, growth in economic wealth corresponds to a decreasing fertility rate, since economic development plays an important role in the demographic fertility transition (Nakicenovic *et al.*, 2000). Population growth has been considered by some to be a key driver in increasing economic welfare, since it brings about a large workforce. However, this is not necessarily the case as other social and institutional factors, such as education and encouraging female work participation, have been shown to be significant in terms of long term economic growth (Nakicenovic *et al.*, 2000). Porritt (2007) has argued that the Peoples Republic of China may have prevented the emission of many millions of tonnes of CO₂ into the atmosphere by implementing its 'one child' only policy. China will not reduce overall annual emissions under any international, post-Kyoto climate change agreement, although it is committed to establishing a 'carbon intensity' target (Cranston *et al.*, 2010). They have also pledged to use 15% of renewable energy sources by 2020, and plant 40 million hectares of new forest as a carbon sequestration measure. But, their

‘one child’ population policy may also have a significant impact on reducing their carbon emissions going forward (Porritt, 2007). China may have refused to adopt targets for GHG reductions under the Kyoto Protocol, but this single population policy may have a significant impact on climate change.

A relationship between economic wealth and environmental quality has long since been mooted amongst researchers (see Chapter 6). The importance of economic development in improving or degrading the environment has been much debated. The standard argument is encapsulated in the ‘Kuznets Curve’ hypothesis (Figure 11-5), whereby environmental protection and economic welfare follow the shape of an inverted-U or bell shaped curve (Huang *et al.*, 2008). This curve shape predominantly represents the situation in those developing countries that have an increasing national income, alongside increasing environmental pressure. As they industrialise, there appears to be a stronger demand for ‘greener’ goods and environmental regulation with the take-up of low impact technology stimulated by the availability of more economic resources for investment. This tends to break down the link between economic growth and environmental degradation, hence the downward turn of the Kuznets Curve.

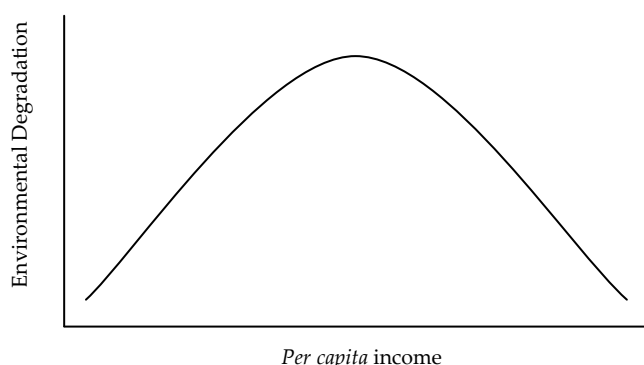


Figure 11-5: Kuznets Curve hypothesis

11.7 SCENARIOS: INDICATORS OF FUTURE PATHWAYS

The contributions to carbon emissions from the respective parameters within the IPAT equation are shown in Figures 11-6 to 11-9. All contributions were taken from a baseline year of 1990. The increase, or indeed decrease, in carbon and other factors is represented by the positive gradient of the trends, and the size of this change is demonstrated by the magnitude of the curves. The y-axis represents the cumulative value of the fractional change of each factor from the base year of 1990.

11.7.1 Past Contributions to Carbon Emissions

Population and economic growth have both historically contributed to the increase in carbon emissions in the industrialised and developing world. Over the 20th century economic wealth has been the major contributor for both regions. Growth in economic prosperity in the wealthy North dominated the emissions of carbon throughout the

century; population played only a small role, indicated by the less steep gradient and smaller magnitude (Figure 11-6). This contrasts with the majority South, where population and economic growth were demonstrated to both be significant drivers of carbon emissions in the 1900s (Figure 11-6).

Population was marginally more significant during the first half of the 20th century for the South, becoming of equal worth by the turn of the millennium. Beyond this point wealth became the more important determinant of carbon emissions. Historically carbon intensity hasn't improved much in the developing world, and thus the carbon emissions trend follows the shape of both the economic and population patterns. For the industrialised world, the carbon emissions were limited by the improved efficiencies illustrated by the decreasing carbon intensity. These past trends are in agreement with those of Gurer & Ban (1997), who have shown that economic prosperity is the greatest contributor to the rise in CO₂ emissions for the OECD.

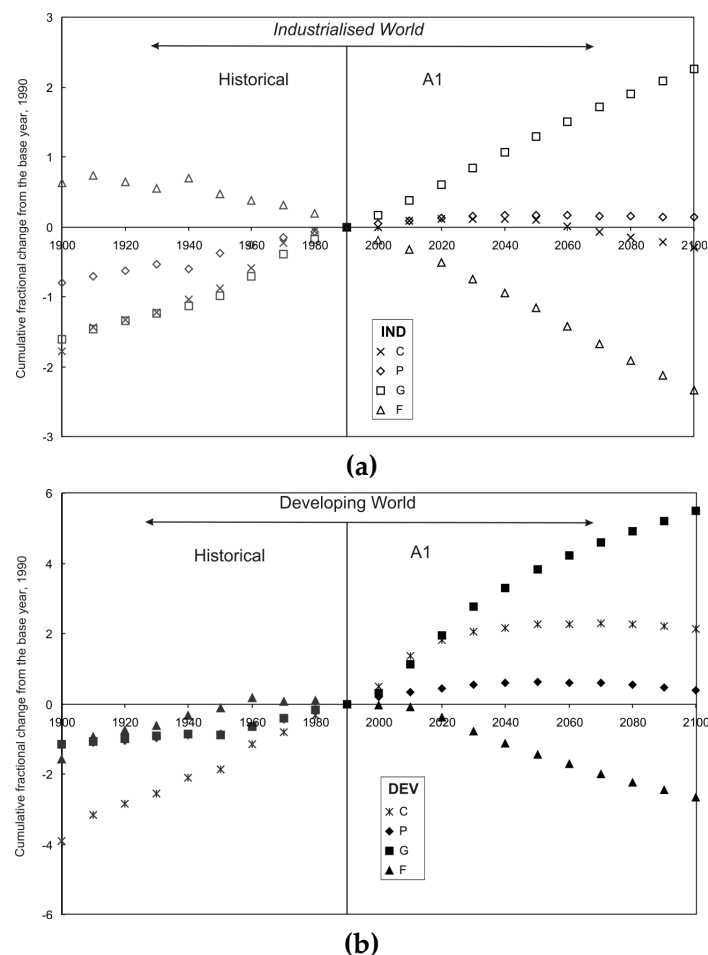


Figure 11-6: North-South Cumulative Change in Carbon Emissions Relative to the Base Year of 1990 - Historic Data and A1 Scenarios for (a) the Industrialised and (b) the Developing World

C represents the carbon emissions, P is population, G is per capita GDP and F is carbon intensity

11.7.2 Future Differences between the North and South

There have been many predictions for the future growth of the developing and industrialised countries, and the way in which this may affect their carbon emissions. The four 'marker' scenarios selected in Chapter 5 were evaluated to assess the different influences of population and economic welfare for the developing and developed worlds to the end of the century.

Economic development was shown to be the largest contributor to growing carbon emissions in the industrialised world under all four marker scenarios (see, for example, Figure 11-6a - Figure 11-8a). The growth rates are high and the magnitude of the values is far larger than those for population. Indeed, Figure 11-6a illustrates that population growth has a much smaller influence on the carbon emissions of the prosperous North. This was expected, as the countries of the industrialised North continue to expand economically, but with a relatively constant population. Despite this increase in wealth, the carbon emissions do not grow exponentially. Instead the carbon intensity effectively reduces the total carbon emissions as efficiency improvements are implemented into the future. For the industrialised world, three of the scenarios indicate that carbon emissions will peak and then fall again by the end of the century (for example, see Figure 11-8a), following the shape of the Kuznet curve. The exception is the scenario A2, which implies greater self-reliance amongst the regions (Figure 11-7a).

Carbon emissions are being pushed up by economic growth, but this is counteracted by improving (reducing) carbon intensity levels. The industrialised world is technologically advanced, and has the wealth to invest in energy reducing strategies. For instance, increased use of renewables enables a better energy mix and therefore fewer pollutants. The A2 scenario was the only storyline with continuously increasing carbon emissions in the industrialised world; this may be due to the underlying assumption that energy intensity reduces later in the century than for other scenarios (Figure 11-7a).

The distinction between the contribution of economic and population growth to future carbon emissions for the developing world from the turn of the millennium is clear. Economic growth is seen to be the dominating factor in causing the rise in carbon emissions (see Figure 11-6b – Figure 11-8b). Population no longer plays such a dominant role in the growing carbon emissions; despite the expanding levels, population in the majority South is predicted to peak and decrease for the A1 and B1 scenarios and growth will slow down for the A2 and B2 storylines. The results here are in agreement with Shi (2003); the impact upon emissions from population growth was far more pronounced in developing countries than in developed countries. Here it is shown that growth in carbon dioxide emissions outpaces population growth in both the

industrialised and industrialising countries, as was highlighted for the period 1975-1996 (Shi, 2003); this was more pronounced in the developing countries.

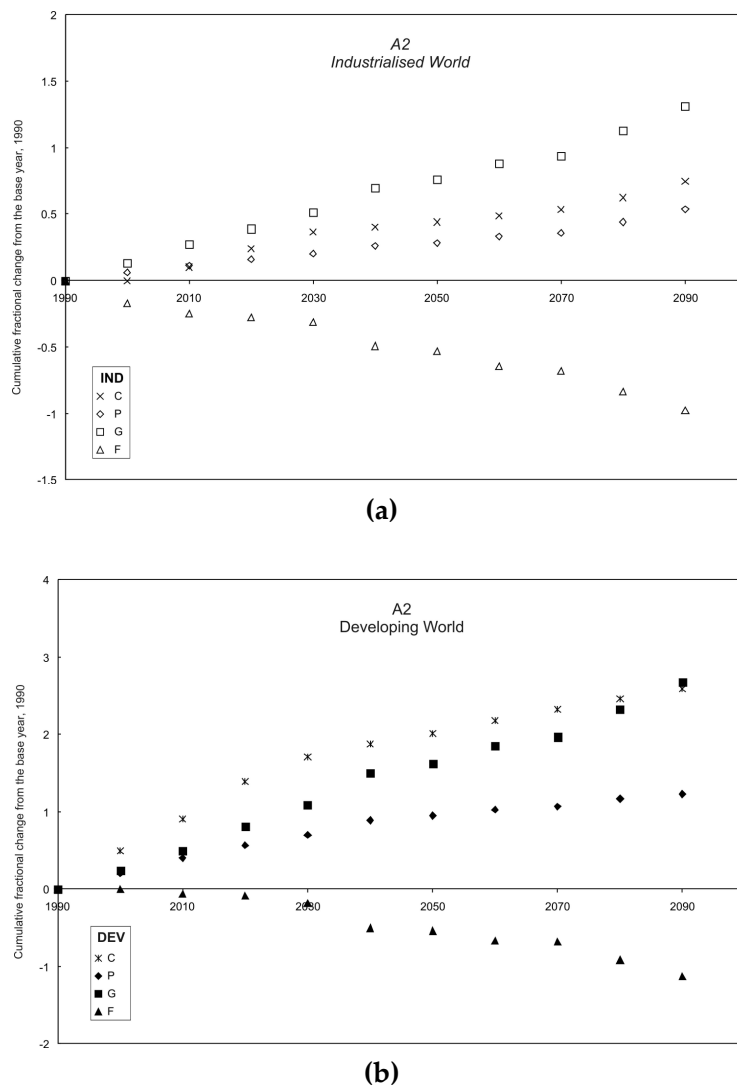


Figure 11-7: North-South Cumulative Change in Carbon Emissions from the Base Year of 1990 - A2 Scenarios for (a) the Industrialised and (b) the Developing World

C represents the carbon emissions, P is population, G is per capita GDP and F is carbon intensity

In a similar way to the industrialised North, the carbon emissions of the developing South are kept from reaching very high levels by improvements in carbon intensity into the future. The B1 scenario (Figure 11-8a), a pathway to a more environmentally conscious world, shows the best reduction in carbon for the industrialised world. Investments are made in green technologies and a focus upon environmental strategies is assumed. The developing world also has a large negative gradient in carbon intensity, which is reflected in the eventual reduction of emissions by 2100. As the developing world industrialises with growing wealth, they should be encouraged to become more efficient and utilise technological advancements to ensure improvements in energy intensity that result in significantly reducing carbon emissions.

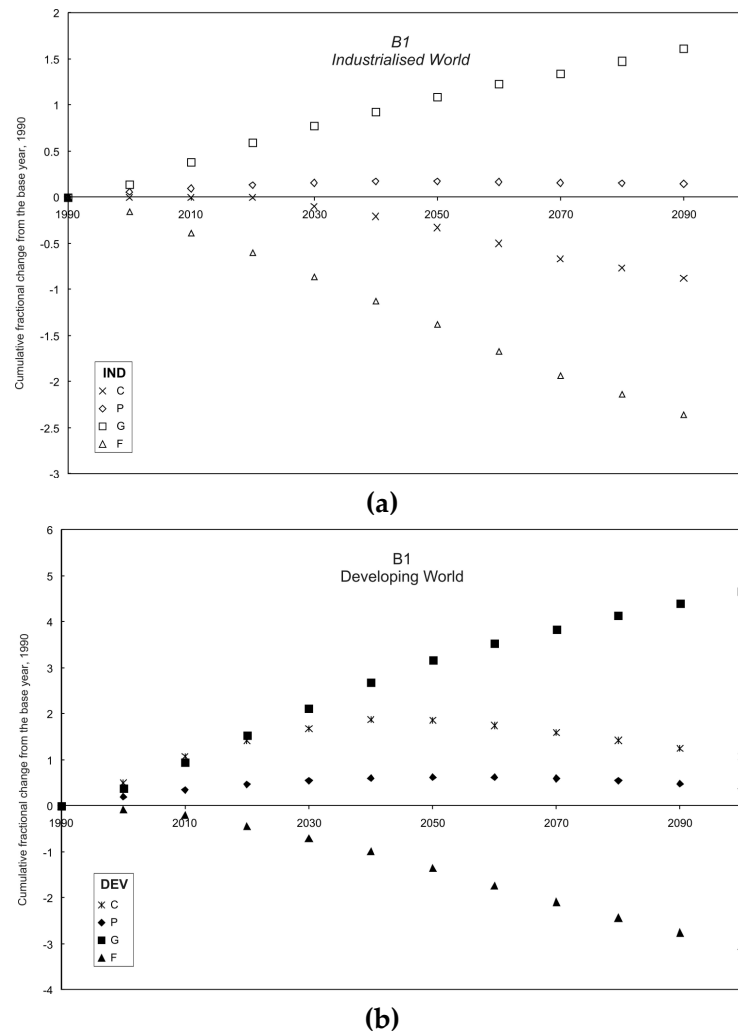


Figure 11-8: North-South Cumulative Change in Carbon Emissions from the Base Year of 1990 - B1 Scenarios for (a) the Industrialised and (b) the Developing World

C represents the carbon emissions, P is population, G is per capita GDP and F is carbon intensity

The growing population and economies within the developing world caused the CO₂ emissions to rise at a faster rate than for the industrialised world. The total carbon emissions peak and begin to decrease for both the industrialised and developing worlds under the A1 and B1 scenarios (compare and contrast Figure 11-6 and Figure 11-8). This is due to the global commitment to sustainability, internationalisation of people, and a convergence of regions implied by these scenarios. The A2 and B2 storylines maintain a positive gradient in carbon emissions for the developing countries (see Figure 11-7b and Figure 11-9b). This is caused by the large growth in population, particularly for A2, with little interaction between regions. Both of these scenarios presume a degree of self-reliance, together with local solutions to energy and environmental problems. There is therefore a slower rate of knowledge transfer and technological advancement that might otherwise encourage improvements in resource efficiency and carbon reduction.

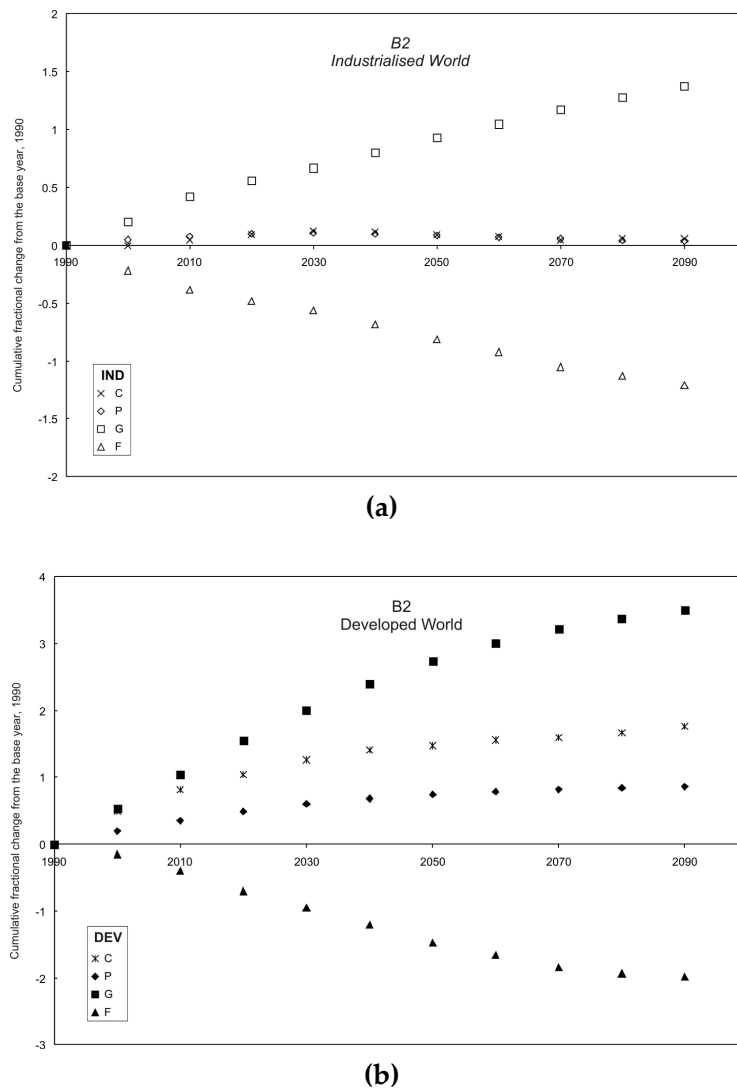


Figure 11-9: North-South Cumulative Change in Carbon Emissions from the Base Year of 1990 – B2 Scenarios for (a) the Industrialised and (b) the Developing World

C represents the carbon emissions, P is population, G is per capita GDP and F is carbon intensity

Kuznet's hypothesis may ring true as the developing world heads towards economic prosperity by the end of the 21st century. Improvement in environmental quality due to diminishing carbon emissions can be seen for the majority of scenarios. The reductions in emissions are most pronounced for the B1 scenario due to the environmental awareness that is related to this storyline. Through industrialisation and economic growth the developing world is able to invest in clean, efficient technologies and encourage environmental regulation.

Chertow (2000) concurs that although population and economic growth have historically been seen as the most damaging factors to the environment, these increases can be balanced by improvements to the environment that are offered through technological systems and advancement. This agrees with the results produced in this chapter, that as energy intensity and carbon ratio are improved they offer an

appropriate balance to the growing economies and populations of the world. Ehrlich & Holdren (1971) have a contrasting view that “if there are too many people, even the most wisely managed technology will not keep the environment from being overstressed”. Commoner (1972) on the other hand argues that technology has created far more environmental pressures and devastating impacts, following the post-war period, than any other factor. These opinions are now outdated and technology has advanced so much that it can no longer be singularly blamed for the rising CO₂ emissions and environmental degradation. Instead there is a tendency towards technological optimism as efficiencies improve and technological solutions offer greater opportunities for careful resource use and reductions in emissions.

It has been shown that population and economic wealth both contribute to the growth in carbon emissions associated with developing and industrialised countries. For the industrialised world, it was found that economic wealth was the most significant driver of CO₂ emissions from both historic trends and future scenarios. In the case of the developing countries, the distinction between population and economic growth was less clear. Historically, population was seen to be a significant driver as wealth, but as the world begins to converge economically during the 21st Century, wealth may start to play a more significant role in affecting carbon emissions as the developing world grows. However, it must be remembered that the build-up of atmospheric CO₂ concentrations is largely a consequence of emissions released by countries of the North since the start of their so-called ‘industrial revolution’ around 1850.

11.7.3 Controversies with Population and Wealth

In some regions of the world the postulated baby boom and population growth will not happen; in fact the population in various areas may actually decrease to surprisingly and worryingly low levels. Fred Pearce (2010) has recently discussed such population crashes in his book ‘Peoplequake’, which may result in a ‘population famine’. Taking Europe as an example, the population is reaching its peak. For centuries this region has seen a continuous growth and the possibility of a serious downturn would be concerning, since, as populations dwindle, there may be a loss of identity and cultures particular to such regions. Already many countries rely upon foreign inputs to maintain their economies and without increasing fertility rates to above the replacement levels this can only become more pronounced. The downward spiral of fertility is dangerous as there become fewer women to procreate and increase population levels again. Much of this decrease in population can be attributed to urbanisation causing a demographic transition. However, Brand (2005) suggests that city living should be encouraged, as it allows rural areas to be replenished and efforts should be made to permanently protect rural environments. The problem remains that many of the developed countries are materialistic and consumer driven and they have little need for large families. Indeed, during and following the economic crisis (IMF, 2009), many couples cannot afford to have children and may simply decide to never reproduce. The advantage for such couples is that help is readily available in terms of family planning

and contraceptives, causing the reduced fertility rates. Many women in the developing world may not want to have children, but do not have the appropriate reproductive health care and access to safe contraceptive medicines. It has been estimated that future populations could potentially be reduced by 400 million people in 2100 if proper family planning was made available to all those that need it (Bongaarts *et al.*, 1990); this was based on findings that over a recent 20 year span family planning in the developing world was able to reduce the current population by approximately 40 million people.

Herein lies the real issue – over consumption. The growing populous within the developing world has long since been mooted as a cause for concern, not only in terms of climate change, but also due to food and resource scarcity. However, in the developing countries large families cannot be viewed in such a black and white negative fashion, they are necessary as extra hands to work and enable support networks for even the poorest of families.

The results shown here highlight that it is economic growth that is apparently causing CO₂ emissions to increase, and not the expanding populations. Despite this, increased affluence enables advancement in technologies and efficient resource use, causing improved energy intensity and carbon ratio levels. As such these results must be considered carefully and with understanding of the underlying factors and their inter-relationships.

As the developing world becomes more affluent it is evident that their associated carbon emissions will increase. However, it can also be argued that in growing economically there comes the benefit of investments in advancing technologies to improve resource efficiency and reduce these total carbon emissions. This is evident in the progression of the carbon intensity value, with a negative gradient (see Figure 11-6 to Figure 11-9), thus reducing the maximum carbon values for all the marker scenarios. It is commonly thought that economic growth and development are vital prerequisites for improving living standards. This is undoubtedly the case for those countries in extreme poverty with starving populations living in utterly unacceptable conditions. However, for the developed world a growth in wealth may not necessarily be advantageous. This is highlighted by using the IPCC A2 scenario for the industrialised world (Figure 11-7a). Carbon emissions are seen to continuously grow despite improvements with efficiencies and technologies shown by the decreasing carbon intensity. The A2 scenario is associated with high economic growth with little investment in environmental protectionism or internationalisation and offers an excellent example of a future world that is highly affluent, but with no consideration for the environmental consequences of humanity's lifestyle choices, resource use or emissions. As such, improving GDP levels may include the positive effects of enabling technological developments to improve efficiencies and make advances in fuel substitutions for example, but this can often be associated with the rebound effect,

whereby costs are reduced as efficiencies better, which by making energy affordable in turn causes an increased resource use overall.

Simms *et al.* (2010) argue that indefinite global economic growth is unsustainable. They use a pet hamster as an analogy. A hamster doubles its weight from birth to puberty each week (six weeks later after birth). If the hamster continued to double its weight every week it would reach a mammoth mass of 9 billion tonnes on its first birthday. In Nature this is not possible as once animals reach maturity their weight levels off; this limitation could be applied to the economy since continuous growth is pushing the planet beyond its natural capital and its safe limits. A change in economies may be necessary for humanity to live within the Earth's environmental budget. This change can be demonstrated with the B1 scenario which has strong environmental protectionism as well as a good level of social consciousness and the reduction of income inequalities is a result of both international and domestic endeavours. For this scenario, carbon emissions are reduced by the end of the 21st century for both the developed and developing nation states. As the developing world completes its industrialisation emissions continue to grow along with wealth, but by the mid century investments are made to reduce carbon dioxide production and move towards a more sustainable world. This can be achieved through the globalisation of peoples and ideas, with an emphasis upon environmental consciousness that is associated with the B1 storyline.

11.8 SUMMARY

The work undertaken within this chapter discusses the significance of various contributing factors to the emission of carbon dioxide. The influence of economic wealth and population are of particular interest and are considered both historically and into the future. The developed and industrialising worlds are contrasted, since they have significantly different population and affluence levels. It is proven that population and economic wealth have historically been key drivers in increasing CO₂ emission for the developing world; however the focus upon economic welfare will increase into this century such that population is no longer a strong driving force. In contrast the industrialised world's CO₂ emissions is driving by wealth, although this is limited by the improvements in carbon ratio and energy intensity.

Aim 2 is achieved by comparing and contrasting the difference between the carbon consumption for the developing and industrialised regions of the world. Objective 7 is implemented by establishing the importance of the IPAT equation and looking at contrasting contributions over a 200 year period.

CHAPTER 12

ONE FOOT IN THE PAST AND STEPPING TOWARDS THE FUTURE

'Look deep into nature, and then you will understand everything better'
(Albert Einstein)

12.1 INTRODUCTION

The following discussion synthesises the results and key findings of the preceding chapters. There were two main aims for this thesis (Chapter 1), the first being to assess the fundamentals of the footprint, both carbon and environmental, and the influential drivers that affect its size and growth. The second was to compare and contrast the differences between the two major regions of the world – the prosperous North and the populous South – and to consider their changing footprints from historic trends through to future patterns, as well as their carbon consumption.

Four major pieces of original research were undertaken (Chapters 8-11) to achieve these aims. These can be considered both as individual contributions, as well as integrated pieces of work that together identify and present coherent research to complete the aims set out for this thesis.

The ecological footprint forms the backbone of this thesis and is developed in terms of its dependencies upon a variety of factors and its application to future world scenarios. This type of analysis is important to highlight and avert the 'boiled frog syndrome', by pushing the boundaries of our understanding of the limits of Nature, our over consumption and global imbalance of resource use.

12.2 DEVELOPING FOOTPRINT DETERMINANTS

Ecological footprints are important, albeit partial, aggregate indicators of a nations' progress along the sustainable development pathway. The footprint is a resource accounting tool that can be used to address underlying sustainability questions and further our understanding of humanity's resource consumption. By considering a host of determinants that influence the footprint, a better appreciation of the power and application of this indicator was established. The footprint has been criticised for being too aggregated an indicator, which oversimplifies the complex issues of sustainability and impacts. Through the analyses undertaken in Chapter 8 and Chapter 9, the footprint is broken down and considered in an original manner, such that it may be more readily understood and appropriately manipulated.

Assessment was made regarding the influential determinants of the *per capita* ecological footprint in Chapter 8 and for the *per capita* carbon footprint in Chapter 9. The correlation of national footprints indicates the extent to which various countries degrade natural capital in generating their national income.

It has been shown, in common with the earlier study by Hammond (2006a), that *per capita* national ecological footprints were strongly dependent on economic prosperity, but only weakly on population density (Chapter 8). Small variations were found in empirical coefficients linking income and population density to the footprint from the original study. Other determinants analysed in the present research were found to be, by and large, proportional to per capita national income. They were eliminated from the correlation process in order to avoid double accounting (the exponents in the 'power-law' correlating equation were set equal to zero). This analysis was developed further for the carbon footprint in the year 2005, and it was shown that there was a strong relationship with economic growth, energy intensity and carbon ratio (Chapter 9).

12.2.1 Implications of the correlating power law expressions

The final 'power-law' correlating equation for *ef* was used to highlight the situation in the G8 + 5 nations (the nation states are identified in Chapter 7). Developing countries were found to have higher energy intensities, but with lower carbon ratios. This was contrasted with developed nations which, despite having lower energy intensities, tend to have higher than average carbon ratios. This implies that the advanced technologies available in the developed world were not leading to a low carbon economy. Greater emphasis will need to be placed on the adoption of low or zero carbon (LZC) technologies, such as energy efficiency measures, nuclear power or renewable energy systems. The 'power-law' correlating equation indicated which specific countries are relatively profligate or frugal in terms of their use of natural capital (see Figure 8-9, pp.110).

It was demonstrated that countries in the industrialised world are associated with a high economic wealth and large carbon footprint trend (Figure 9-1, pp.120). These countries currently dominate the global economy and attribute the largest percentage towards the total world's ecological footprint (Figure 9-6, pp.125). However, countries such as India and China which are industrialising rapidly and are fast becoming serious contenders not only in the world economy but also in terms of their vast total carbon emissions. A look into the future through the IPCC scenarios (Nakicenovic *et al.*, 2000) and Cranston & Hammond's analysis (2010b) indicates these transitional economies will quickly begin to dominate the market (see also Chapter 10). This may translate badly with respect to CO₂ emissions as such countries are not supported with new clean technologies but rely heavily on the polluting coal fired power stations of the Industrial Revolution. Already it has been shown that these countries are profligate with their resources, as they are located above the correlating 'power-law' *cf* equation (Figure 9-5, pp.123). This equation accounts not only for the economic prosperity of each nation

state in relation to its *per capita* carbon footprint, but it also includes the amount of carbon released per joule of energy (the Carbon Ratio) and the intensity of energy used per \$ (the Energy Intensity). If these ratios can be improved, the emission of carbon may be reduced. Early adoption of renewables will encourage best practice within the developing nations.

The natural capital of planet Earth cannot replenish itself quickly enough to overcome the large deficit that is growing with every year and, on its current trajectory, will eventually no longer be able to cope with the demand. It has been illustrated that there is a vast difference in demands upon Nature's resources between the developing and industrialised countries (Cranston *et al.*, 2010; Cranston & Hammond, 2010b) (Chapters 8-10). The world as a whole is currently in an overshoot condition, whereby humanity demanded almost 30% more biological capacity than the world's ecosystems were able to regenerate in the year 2005 (WWF International, 2008). This ecological debt emphasises the need to bring the global consumption levels and pressure upon the planet's regenerative capacity to an appropriate and acceptable limit. A similar pattern has been noted for carbon dioxide emissions (Cranston & Hammond, 2010a) (Chapter 11), and a framework to reduce these wastes has been set up through the Kyoto Protocol. Overshoot was used to highlight those countries in ecological debt, and those that are in credit (Cranston *et al.*, 2010) (Chapter 8). The world as a whole is currently in ecological deficit, demanding far more resources in a year than Nature is capable of producing. There must therefore be a balance, not only in terms of the developing and developed world, but also in terms of ecological debtors and ecological creditors as humanity heads into the future.

12.3 SHARING THE BURDEN

In order to achieve global sustainability a serious commitment to GHG emissions reduction is required, and a greater dedication to environmental protection in both the industrialised North and the populous South. However, there is an issue of intergenerational equity in relation to the contribution of the developed world. CO₂ has a residence time in the atmosphere of around 100 years (Hammond, 2000). The build-up of atmospheric concentrations is therefore largely a consequence of emissions released by countries of the North since the start of their so-called 'industrial revolution'. The industrialised nations should take a lead in mitigating the global release of GHGs, because they are principally responsible for their life-time concentrations (Chapter 11).

Chapter 11 acknowledged that there has been some contention regarding which factors are contributing most heavily to the increases in CO₂ emissions, with particular reference to the contrasts between the North and South regions of the world, one being vastly affluent, the other vastly populated. Historic data and future scenarios from the IPCC *Special Report on Emissions Scenarios* (Nakicenovic *et al.*, 2000) were used to analyse the changes in emissions caused by varying demographics and wealth. Chapter 11

demonstrated, using a decomposition of the terms in the IPAT equation, that population and economic wealth both contribute to the growth in carbon emissions associated with developing and industrialised countries. For the industrialised world it was found that economic wealth was the most significant driver of CO₂ emissions from both historic trends and future projections. In the case of the developing countries the distinction between population and economic growth was less clear. Historically population and economic growth were seen to be the main drivers, but as the world begins to converge economically during the 21st century, with the growth of the developing world, wealth may start to play a more significant role in affecting carbon emissions.

It was concluded that economic growth is the dominant driver of the carbon emissions in the industrialised regions. With this strong link between carbon emissions and wealth, it is interesting to note the effects of the economic recession (IMF, 2009) with respect to CO₂. The financial crisis has had a significant impact upon the global energy sector, such that investment in polluting technologies has been postponed and emissions in 2009 were thought to fall by up to 3% (IEA, 2009a; IEA, 2009b). If this trend to continue, emissions in 2020 would be 5% lower than that predicted by the IEA in 2008 (IEA, 2009b). These effects were not taken into consideration due to the limited data availability, particularly regarding long term scenario projections and differing effects across the North and the South regions of the world.

The results showed that as the developing world heads towards industrialisation at the end of the 21st century, economic prosperity is likely to have a far greater impact on annual carbon emissions than population growth. The growth in population size and economic wealth in the developing world will eventually cause carbon emissions to rise at a faster rate than the industrialised world. Similar observations were recently made by Raupach *et al.* (2007) in their study of the drivers of carbon emissions both globally and in a number of sub-regional groups. The improvements in energy efficiency and resource productivity counteract the effects of the growth in wealth and population on rising atmospheric carbon concentrations. As technological advances are implemented, the energy intensity will fall, resulting in a reduction in the carbon emissions for each region. The sharing of ideas and knowledge between the industrialised and developing world is therefore crucial to ensure worldwide GHG pollutants are kept below dangerous levels in order to prevent further damage to the global climate system. Chertow (2000) discussed the importance of technology in improving the environment. It is acknowledged that although an increasing population and economic wealth trend can be damaging to the environment, it may actually offer technological solutions to alleviate some problems.

12.4 ENVIRONMENTAL EQUITY

Environmental sustainability could and should, on equity grounds, be aided by the transfer of best practice energy technologies from the richer to the poorer regions of the world (Hammond, 2000). These issues are at the heart of international negotiations aimed at providing a successor to the Kyoto Protocol, originally established under the United Nations auspices to stabilise GHG concentrations at a level that would prevent dangerous climate change. A new agreement will hopefully come into being post-2012 that will ensure a sustainable future for the people and wildlife on 'Spaceship Earth'.

As the transitional countries grow in geopolitical power and become key economic players, it becomes necessary to consider how best to implement action against climate change. There must be a willingness from these nation states to commit to such achievements and an agreement from the industrialised world to aid development in a less polluting manner by the transfer of knowledge and the sharing of technologies. Managing such a transition is complex, but should be led by the industrialised countries as they pave the way towards global carbon reductions and sustainable living. The developing world can then follow suit at a slower pace according to their affordability. This could result in the 'Contraction and Convergence' pattern discussed by Meyer (2000) and potentially demonstrated by the B1 marker scenario in Chapter 10.

It was established in Chapter 10 that there is an imbalance between resource use and the availability of natural capital, and also an inequity within regions of the world in terms of the use of Nature's supplies. Scenarios were adopted to assess the possible future pathways for the developing and industrialised countries of the world in terms of their ecological footprint. The *ef* correlating 'power-law' equation was adapted to develop a range of future alternatives for the globe. Scenarios from the IPCC (Nakicenovic *et al.*, 2000) were utilised giving four distinctly different routes into the future.

The footprint projections presented in Chapter 10 suggest that a reduction in the consumption of biophysical assets across both the developing and industrialised world is indeed possible. The majority South will dominate the world's ecological footprint well into the 21st Century as it develops and grows to meet the aspiration to improve the well-being of its peoples. The developing world's footprint overshoots that of the industrialised region by around 2010-2015. It then levels out and starts to fall, on the most optimistic scenario (B1), by about 2050.

In order to achieve the declines indicated, particularly by the B1 scenario, within the 21st Century, a serious commitment to GHG emissions reductions would be required, and a greater dedication to environmental protection in both the industrialised North and the majority South. This commitment must not only be in terms of a reduction of the *per capita* footprint, but also in terms of total ecological footprint as shown on a global scale

for A1 and B1 in Figure 10-10. That implies balancing population growth, economic well-being, and environmental impacts.

The B1 and A1 projections for the developing world showed a turndown in the total ecological footprint, and this was mirrored by the industrialised world for these storylines. It appeared that the industrialised North will undergo a change in their energy use and carbon emissions resulting in either a plateau in its total footprint, or indeed a reduction. The outlook for the developing world was less promising, as two scenarios (A2 and B2) showed significant increases in total footprint with little evidence of a deceleration. However, if this region can be encouraged to be more environmentally conscious, there may be a chance to produce a shrinking footprint.

Humanity and Nature need a global future. There are no boundaries in the planetary atmosphere with global warming but there are boundaries for nation states and the discrepancy and competition between nations can have negative effects. Perhaps there is a need to replace competition with co-operation. This is advocated by the B1 and A1 marker scenarios (Chapter 10) where global agreements and national targets encourage a worldwide coalition. The B2 and A2 storylines focus upon local commitments and initiatives with little international collaboration, resulting in poor footprint reductions.

All nations should be encouraged to work together for a total contraction in carbon emissions and converge to an acceptable level. It has been suggested that countries will fall into one of three categories with regard to their regime towards climate change and reducing their carbon footprint (Nuttall & Manz, 2008); those that are willing and able to adjust to serious climate change, those that are willing to change but have economic difficulties in doing so and finally, those that are not willing to partake in combating the problem. It is generally accepted that western economies fall into the first category, whilst the so called 'BRIC' nations (Brazil, Russia, India and China) may fall into the second. Others will be associated with the third group, but it is important that all nations collaborate to combat our damaging effect on the environment.

12.5 TAKING A WALK IN THE WORLD'S SHOES

Chapter 4 highlighted the global inequity associated with the acquisition of the world's resources. It has been illustrated that the richer, more developed countries are the primary cause for the current global ecological debt. It is inevitable that, as the poorer countries aspire to become more industrialised, the vision of a 'better' way of life will result in a larger global footprint, a growing ecological deficit, and a rising overshoot ratio. A consequence of the rapidly growing world population is the continuing overshoot of available natural resources.

Developing countries need to have the opportunity to grow and converge in terms of living standards with the industrialised countries; it should not just be a case of

increasing their economic welfare and enabling industrial boom. Indeed Global Footprint Network expresses the “right to develop” for many countries, which often leads to the “right to collapse” (Global Footprint Network, 2010b) through the overuse of natural resources and stretching Nature’s budget beyond its realistic limitations. Development must be undertaken in an equitable way, with a focus upon careful environmental management, as demonstrated for example through the marker scenario B1. Chapter 10 identifies this scenario as offering potential for both the developing world and the industrialised world to work together to improve our global environmental situation and footprint, move along the pathway towards sustainability and step out of overshoot. This is further underlined in Chapter 11 which highlights the limitations and eventual decrease in carbon emissions that may be possible with improvements in efficiencies, shared ideas and technologies. Throughout these chapters other marker scenarios have been used to offer situations that are less positive: the A2 marker situation for example, which has very little potential for reducing humanity’s footprint in either the populous South or the affluent North. Such examples show that with little international co-operation growth is not only stilted but there is little development towards environmental consciousness. Regional development is important and nations should strive to develop internally, but the overarching global picture should also be considered. The effects of climate change will impact on many more countries in the developing world than the industrialised world, and there is therefore a huge incentive for change. Chapter 9 demonstrated that the developed world is to blame for the huge accumulation of carbon dioxide in the atmosphere, and discussed the idea that the developing regions must be allowed to develop, but this must be achieved through carefully managed environmental measures without exacerbating the current situation. The footprint has been implemented to demonstrate different future trajectories (Chapter 10) and how humanity may be able to reduce its consumption to move beyond overshoot to an equitable and environmentally sound global situation.

CHAPTER 13

CONCLUSIONS

13.1 MEETING THE OBJECTIVES OF THE RESEARCH

Sustainable development is necessary for equitable growth with respect to the Earth's natural resources. A balance between the developing and industrialised regions of the world is necessary to ensure growth is facilitated in a fair and measured manner. The ecological footprint is a tool that enables this measurement and demonstrates how far along the sustainable pathway nation states have come. This thesis aimed to develop the environmental and the carbon footprint by investigating the key determinants that influence its size and shape. A wide range of factors were considered and 'power-law' correlating equations were finalised. These were adapted in conjunction with scenarios from the IPCC's *Special Report on Emissions Scenarios* to assess different routes to the future not only for the world as whole, but to consider the stark variations between the developing and industrialised worlds. Having established the fundamental differences, an assessment was undertaken by developing the IPAT equation to determine which factors most strongly impacted the growth of carbon emissions. This analysis also highlighted the dissimilarity of the two major regions of the world.

13.2 KEY FINDINGS

- Correlating equations have been developed for the carbon and ecological footprint. These highlight the significant impact that economic wealth has upon the footprint, driven by humanity's consumerist behaviour.
- The definition of the carbon footprint is confused; however, it remains a useful indicator and through more detailed development it can become a powerful tool.
- The driving force behind carbon emissions was concluded to be economic growth, for both the developing and industrialised world, particularly looking at future scenarios.
- Future transition pathways have been identified and it was shown that there is the potential for a balance between the prosperous North and the majority South in terms of their footprint patterns, leading to an overall global reduction.

Economic welfare was proven to be the most significant factor influencing the carbon and ecological footprints for the present and well into the future. The correlating

'power-law' equation returned a very strong relationship between the footprint and affluence, such that many other variables had to be eliminated from the final expression. This result deepens understanding of the footprint indicator as it shows that those wealthier, consumer driven nation states have far higher footprint values. Population density was also included within the final ecological footprint equation, highlighting the influence of population growth upon footprint size, particularly when considering total footprint values.

When this analysis was undertaken for scenarios in the future, the relationship between the ecological footprint and additional variables became apparent, and indeed influential. Energy intensity and carbon ratio play an important role in reducing footprint values towards the end of the century, particularly for scenarios that have an enhanced environmental awareness. Therefore these factors were included in the footprint equation that bound the entire twenty-first century. Economic welfare was still the most dominant factor, but from such results it was concluded that with the potential for investment in green technologies and the global sharing of ideas, the total footprint results may have the possibility to shrink.

The common portrayal of the carbon footprint is not a footprint, but a mass. The significance of this fundamental difference was analysed and the importance of the carbon indicator was shown. The 'carbon weight' was proven to have a very similar value to the carbon footprint, due to the conversion factor of approximately 1. This could have the advantage of enabling those who understand the complexity of the footprint to readily convert between the 'weight' and 'footprint' values.

The IPAT equation was disaggregated into its individual components so that the contributions from population, wealth and energy use and efficiency were each assessed with respect to growing carbon emissions for four marker scenarios up to 2100 and historic trends from 1900. It was concluded that population and economic wealth both had negative impacts upon the carbon emissions for the developing world in the previous century, but that as humanity heads towards the year 2100 the impact of economic growth is far more predominant than population. The industrialised regions have always shown an enhanced contribution from economic wealth which influences high carbon values. These results show that economic growth should be controlled and encouraged in a sustainable manner. Energy efficiency was shown to have tremendous impact in maintaining lower carbon values, therefore limiting total emissions.

The correlating ecological footprint equations were developed and adapted to take account of future changes in the prosperous North and populous South. Investigations of the two regions for the four marker scenarios resulted in some contrasting findings. It was concluded that only one scenario offered the potential for a contraction and convergence trend, whereby the North and South regions are finally at an equal

ecological footprint level, which is lower than the current value for wealthy countries. This is not possible within this century, but the patterns indicate that it may occur in the twenty-second century. Other scenarios were far less optimistic and the footprint results for the scenarios with little international integration showed continuously expanding footprint levels for the Northern and Southern regions. It was determined that in order to achieve global equity and sustainability there must be a greater awareness of environmental issues and improvements both within regions and across regions.

13.3 CONTRIBUTIONS OF THE THESIS

The main contributions of this thesis have been highlighted by the key findings in section 13.2. By achieving the original aims set out at the start of the thesis it can be concluded that these contributions successfully assessed the fundamentals of the footprint, in terms of the determinants that influence its size and growth (Aim 1) and that the footprints and the carbon consumption was compared and contrasted between the populous South and the prosperous North, not only in the past but into the future (Aim 2). Correlating 'power-law' equations were developed for both the carbon and the ecological footprint, based upon a host of different variables. The contribution of these studies was to prove that the footprint is primarily and inextricably linked to economic welfare. This result was further highlighted in the study assessing carbon contributions. These equations were applied to four different scenarios which identified significantly different future worlds by the turn of the next century.

The value and limitations of the footprint should be considered with regard to the scenarios. This analysis was undertaken in a purely mathematical manner, and used only the footprint to extrapolate trends into the future. The footprint is an useful indicator so show how resource use and overconsumption may change into the future, but it is not able to capture the effects upon, for example, species and biodiversity, or upon the well-being of the human race. As such, although this contribution is informative, it must be utilised in harmony with other indicators, which may include for instance, the Human Development Index.

13.4 RECOMMENDATIONS FOR FURTHER WORK

There is scope for further work following the research undertaken within this thesis.

- The limitations of the footprint have been discussed. It would be advantageous to consider other indicators alongside the footprint and contrast how they reflect the 'Three Pillars' of sustainability. Such indicators could include the Human Development Indicator. This would ensure that all aspects of sustainable development are investigated and there is a balanced argument particularly when assessing the fundamental differences between the developing and industrialised nation states.

- Analysis regarding the correlating power law equation for the *per capita* ecological footprint covered a vast range of determinants. The footprint was compared to available biocapacity in order to determine ecological overshoot, and a similar investigation could be undertaken to the key driving forces behind the changes in biocapacity. This could also be done with respect to biodiversity.
- Having established the correlating power law equation for *per capita* national carbon footprints it would be useful to develop this further such that future prediction for changes in carbon footprints can be predicted, just as was undertaken for the ecological footprint.
- The scenario predictions for the North and South regions of the world have the potential to add levels of detail. The methodology is currently limited to the mathematical manipulation of the correlating equations and data availability. A parallel study focusing upon building the footprint from a top down or bottom up situation using not only energy, emission, population and economic predictions but including dynamic changes in climate, land use and demographics would offer a different insight to such a complex problem.
- Having made estimates for the footprint into the futures, it would be novel to calculate the biocapacity changes to the end of the century as well. This would enable a study regarding the dynamic nature of ecological debt across the globe and within the developing and industrialised nation states.

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APPENDIX A

PUBLISHED PAPERS

The following papers have been published or are currently in press. The first four are reproduced in this appendix.

- pp. 206-225** Cranston, G.R., G.P. Hammond and R.C. Johnson, 2010. 'Ecological Debt: Exploring the Factors that Effect National Footprints', *Journal of Environmental Policy and Planning*. 12 (2): 121-140.

This paper is a revised and updated version of the paper 'Exploring the factors that influence national ecological footprints' originally presented at the *International Ecological Footprint Conference: 'Stepping Up the Pace'*, Cardiff, Wales, 8-10 May 2007, Paper M94.

- pp. 226-232** Cranston, G.R. & G.P. Hammond, 2010. 'North and South: Regional Footprints on the Transition Pathway to a Low Carbon, Global Economy', *Applied Energy*. 87 (9): 2945-2951.

This is a revised version of a paper originally presented at the *First International Conference on Applied Energy: 'ICAE'09'*, Hong Kong, 5-7 January 2009, Paper 029.

- pp. 233-254** Cranston, G. R. & G.P. Hammond, 2010. 'Egalité, fraternité, soutenabilité: evaluating the significance of regional affluence and population growth on carbon emissions'. *International Journal of Global Warming*. 2 (3): 189-10.

This is a modified version of the paper 'Population and Economic Growth: Assessing the Principal Determinants of Carbon Emissions' presented at the *Global Conference on Global Warming 2009: GCGW*, Istanbul, 5-9 July 2009, Paper no: GCGW-09-400.

Journal of Environmental Policy & Planning
Vol. 12, No. 2, June 2010, 121–140



Ecological Debt: Exploring the Factors that Affect National Footprints

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ABSTRACT Environmental or 'ecological' footprints have been widely used as aggregate indicators of the human appropriation of natural capital with prevailing technology. They represent a partial measure of a community's pathway towards sustainable development. Footprints vary between countries at different stages of economic development and varying geographic characteristics. Dimensional analysis techniques from engineering and the thermal sciences have been employed to determine the influence of a wide range of parameters on per capita national footprints, including per capita national income, population density, pollutant emission intensity, local climate, soil productivity, and technology. One hundred and nine countries made up the final database (based on 2003 international statistical data sets). Per capita national environmental footprints are found to be strongly dependent on per capita national income, and only weakly on population density. The implications of the findings are illustrated by reference to the situation in the G8 + 5 nations. Variations about the resulting power-law correlation suggest the extent to which individual nations are frugal or profligate in terms of their resource use and environmental impacts. The ecological debt owed by the industrialized countries of the North to the developing nations of the populous South is highlighted.

KEY WORDS: Ecological debt, environmental footprints, biocapacity, resource use, gross national income, population density, international development, sustainability

Introduction

Environmental or 'ecological' footprints are a simple, yet graphic measure of the resources consumed and the wastes produced by a given population with existing technology (in global hectares (gha)). Ideas of this type were first brought to prominence by Georg Borgstrom using the term 'ghost acreages' (Borgstrom, 1972), a measure of biocapacity (in hectares (ha))—the capacity of a biologically

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1523-908X print/1522-7200 Online/10/020121-20 © 2010 Taylor & Francis
DOI: 10.1080/15239081003719193

productive area (land or aquatic ecosystem) to generate an on-going supply of renewable resources and to assimilate wastes. Around the same time, William Rees developed what he termed the 'regional capsule' (subsequently renamed as the 'ecological footprint') to teach planning students the importance of environmental accounting. His work led to the now popular approach detailed in *Our Ecological Footprint* (Wackernagel & Rees, 1996). The total footprint area is expressed as a standardized average biologically productive hectare of land (the 'global hectare'), such that different populations and land areas may be comparable one with another. Environmental footprints offer an aggregate indicator of how successful countries are in moving along a pathway towards 'sustainability'. By taking a snapshot of our current ecological demands, it was envisaged that footprint analysis would illustrate the burden that humanity places on the environment in absolute terms, as well as providing a useful benchmark to compare the success of alternative sustainable development strategies at global, regional, and national levels. Thus, environmental footprint analysis (EFA) provides a useful indicator of the environmental performance of nation states and other communities, as well as showing how far along the sustainable development pathway each has travelled.

Footprints vary between countries at different stages of economic development and varying geographic characteristics. Recently, Hammond (2006) postulated that per capita national environmental footprints might be a function of a range of variables: population density, national income, energy intensity, and carbon emissions (where $\text{carbon} = 12 \times \text{CO}_2 / (12 + 32) \sim 0.273 \text{ CO}_2$, on the basis of molecular weights). He correlated these parameters based on international data for the turn of the millennium (that is approximately 1999–2000) for a data set of 113 nation states. The resulting 'power-law' expression, derived using the sort of 'dimensional analysis' techniques widely used in engineering and the physical sciences, indicated the relative significance of these factors. Hammond (2006) demonstrated that per capita national environmental footprints are strongly dependent on per capita national income and only weakly on population density. He thereby illustrated the underlying relations within the North–South environmental and development nexus.

The present study has re-examined the issues considered by Hammond (2006), but employing a much wider range of possible dependent variables and more recent data sets. Environmental footprints for developed and developing countries from around the world have therefore been analysed. Footprint data produced for the World Wide Fund for Nature (WWF) in their *Living Planet Report 2006* (Loh & Goldfinger, 2006) were utilized, along with a wide variety of other international data sets available for the year 2003. The determinants of these environmental footprints were again evaluated using scaling arguments, here cross-checked via multi-linear regression. An aggregate data set for 109 countries was established from these various databases that provided statistical indicators of per capita environmental footprints, population size, land area, national income, energy use, carbon emissions, soil fertility and climatic factors, terrain, and latitude. National climates were represented in terms of average temperatures and precipitation. Variations about the resulting 'power-law' correlation suggest the extent to which individual nation states are currently frugal or profligate in terms of their resource use and environmental impacts. They highlight the need to live within the biocapacity of the planet in order to achieve what is often termed as 'sustainable development'.

The focus here is specifically on the G8 + 5 group of nations, whereas Hammond (2006) highlighted the situation in fifteen nations out of a full data set of 113 countries (for 1999–2000). The latter were arbitrarily distributed across a range of high-, medium- and low-income countries. In contrast, the G8 + 5 group includes the industrialized (mainly ‘high income’) countries (Canada, France, Germany, Italy, Japan, the Russian Federation, the United Kingdom (UK), and the United States of America (USA))—the G8—plus five of the largest ‘emerging’ (mainly ‘middle income’) economies of the developing world: Brazil, the People’s Republic of China (PRC), India, Mexico, and South Africa (Figure 1). They are viewed as being a stronger and more representative grouping than the G8. When the G8 + 5 group were formed in 2005, it was hoped that they would provide fresh stimulus for the so-called Doha Round of international trade talks, and revitalized co-operation aimed at the climate change mitigation. The G8 industrialized nations are located in the geographic North of the planet (see again Figure 1), whereas the five emerging economies are situated in the populous, or ‘Majority’, South, accommodating about 80% of the human population. Thus, the G8 + 5 grouping was seen as providing a new paradigm of future international co-operation. A process of permanent dialogue between the G8 + 5 nations was fully institutionalized in 2007 under the so-called Heiligendamm process, named after the German town where it was agreed. In the light of the world financial ‘credit crunch’ of 2008–2009, the programme of the G8 + 5 nations has concentrated on the impact of the consequent economic downturn in the context of the key challenges arising from energy security, global warming, land use change, and population growth projected to rise by a further 3 billion (to around 9 billion people worldwide) over the twenty-first century. The current statistical data set contained 109 countries in total (for the year 2003), as noted above, from which the situation in the G8 + 5 nations is highlighted.

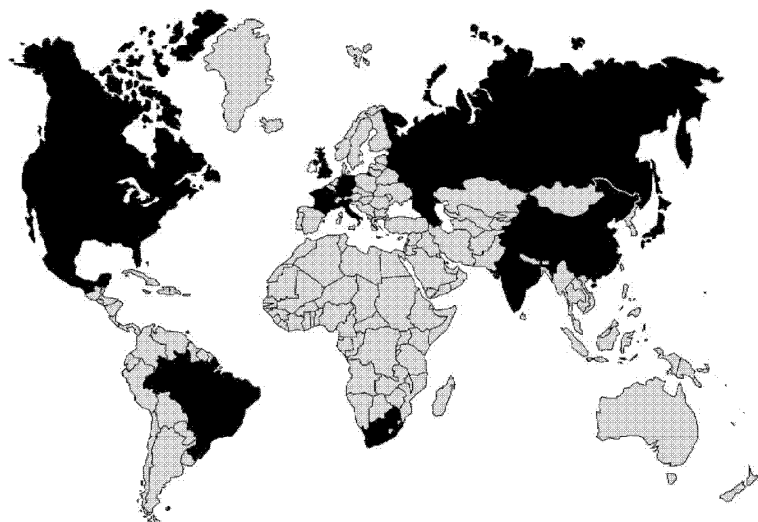


Figure 1. The G8 + 5 group of countries superimposed on the world map. (The G8 nations (l → r): USA, Canada, France, UK, Germany, Italy, Russia, and Japan; the five large emerging economies: (l → r) Mexico, Brazil, South Africa, India, and China).

Defining Sustainable Development

According to Parkin (2000), there are some two hundred separate definitions of 'sustainable development'. The 2002 World Summit on Sustainable Development in Johannesburg adopted the strapline 'people, planet, prosperity' to reflect the requirement that sustainable development implies the balancing of economic and social development with environmental protection: the so-called 'Three Pillars'. The notion originally came to the fore as a result of the Brundtland Commission in the 1980s, which defined it in terms of the need to ensure 'that development meets the needs of the present without compromising the ability of future generations to meet their own needs' (World Commission on Environment and Development (WCED), 1987). Others have argued, for example, that in order to live in a sustainable world, society's demand on nature should be in balance with nature's capacity to meet that demand (Global Footprint Network, 2006). This implies that, to a large extent, development needs to be overshadowed by the 'environmental pillar'. An alternative approach stems from the work of Herman Daly, a well known 'ecological economist', who defines 'growth' as an increase in economic size through material accretion, and 'development' as the realisation of fuller and greater potential (Daly, 1991). Consequently, in his terms, sustainable development aims at progressive social betterment without growing beyond the available biocapacity.

Parkin (2000) and Porritt (2000) have stressed that sustainable development is only a process or journey towards a destination, which is 'sustainability'. This end-game cannot easily be defined from a scientific perspective, but recently Graedel and Klee (2002) have attempted to establish a quantifiable, long-term target for sustainability from an 'industrial ecology' perspective. They suggest a framework, or series of steps, to permit the establishment of the sustainable (or limiting) rate of natural resource use, which can then be contrasted with the current rate of consumption. The Graedel and Klee procedure requires the establishment of equal planetary shares of materials/emissions on a 50-year timescale. They acknowledge that the idea of an 'Earth share' or quota of this sort is controversial, and that the chosen timescale is somewhat arbitrary. Hammond (2006, 2007) has suggested that environmental footprints may provide an alternative quantitative indicator that might be able to better track humanity's pathway towards sustainability. Thus, such footprints indicate the degree to which biophysical limits have been approached or exceeded (Costanza, 2000). They are a partial measure of sustainability in the sense that they correlate well with the economic and environmental pillars, but not so with the social one (Hammond, 2006). The latter requires different qualitative social indicators.

Environmental Footprints and their Correlation

Background

Environmental footprinting has become a popular tool that can illustrate the way in which resources are consumed and wastes produced by a defined community. It is often referred to in the media. Despite it being a relatively recent formulation, it has been widely adopted in the context of education and awareness campaigns, as well as in the development of public policy (Simmons *et al.*, 2000). The terms 'environmental' and 'ecological' footprints are used interchangeably here, although the former is preferred (as suggested by Doughty & Hammond, 2004).

Ecology is that branch of biology dealing with organisms and their natural surroundings. 'Human ecology', sometimes used for the study of humans and their environment, is closer to the usage implied by footprint analysis.

EFA is a tool that is used to estimate the land area required to sustain a given population, e.g. nation states and other communities. It is closely related to an analogous parameter known as the 'environmental space', which is defined as 'the share of the planet and its resources that the human race can take' (McLaren *et al.*, 1998). Most modern communities are far from self-sustaining, but exist only by drawing upon the resources beyond their borders in the surrounding bioregion or 'hinterland' (Doughty & Hammond, 2004; Eaton *et al.*, 2007; Rapport, 2000). It is clear that even primitive hunting and gathering peoples were dependent on a much larger area than their immediate vicinity. Footprint analysis represents only the resource consumption and waste arising from the activities of a specific population. If one country (e.g. the PRC) were to export a product to a different country (say the USA), then the resources and wastes associated with that product will be attributed to the US environmental footprint and not to the Chinese one. This can be demonstrated via a simple equation for the 'consumption footprint' (Hammond, 2006; Loh, 2002; Loh & Goldfinger, 2006):

$$\text{National environmental footprint} = \text{Production footprint} + \text{Imports} - \text{Exports},$$

where the imports and exports are converted into a footprint equivalent basis.

EFA calculations involve several steps. The land area appropriated per capita is broken down into different categories of ecological space (see also Figure 2):

- biodiversity land;
- bioproductive (including arable, forestry, and pasture) land;
- bioproductive sea;
- built or degraded land;
- energy land

This breakdown is chosen because they reflect the categories employed for many primary data sets (Chambers *et al.*, 2000; Eaton *et al.*, 2007). Equivalence or yield factors are then used to convert different area types into the equivalent average biologically productive land in global terms, using the global hectare (gha). This average biological productivity, or 'bioproductivity', is normalized as having an equivalence factor of one. Countries will obviously vary in the extent to which the bioproductivity for each category may be more or less productive when compared with the global average for the same type of land. This enables account to be taken of varying bioproductivity of each land type. For example, cropland will have an above-average bioproductivity with an equivalence factor greater than one. In contrast, grazing land is less productive, and will therefore have an equivalence factor less than one. Yield factors are thereby used to adjust each category in relation to the local yield. Using the global hectare enables direct comparison between nation states.

Footprint analysis offers a snapshot of the current demands on natural capital. The technique does not account for the 'social pillar' of sustainable development, i.e. social inequalities or poverty between nation states and societies. Some have criticized the fact that environmental footprints are calculated on the basis of prevailing technology, for example Ayres (2000). Technological enthusiasts argue

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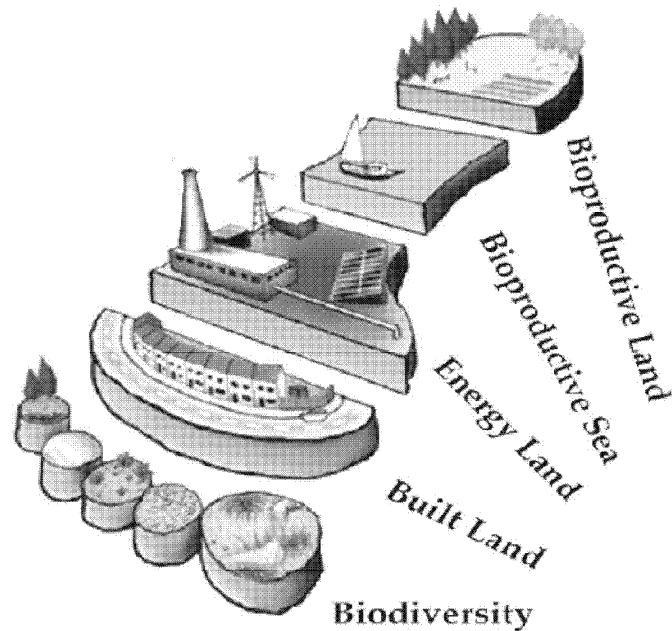


Figure 2. Schematic representation of the environmental footprint, and its land types.
Source: Eaton *et al.* (2007), adapted from Chambers *et al.* (1999). Reproduced with permission of the copyright owner.

that technology fixes will be able to overcome biophysical constraints faced by humanity. Clearly innovation and technological development are key factors in driving economic growth. Given that footprinting only provides a static (1 year at a time) analysis, it is difficult to take into account either underpinning technological changes or the adaptability of social systems. Moffatt (2000) has even argued that using EFA is nothing more than an attention-grabbing tool. However, raising awareness of the human use of resources and generation of waste by this means certainly provides benefits in terms of greater understanding. It is still an important indicator of the effects humanity has on nature's limited resources.

Estimating the environmental footprint of a population—be it for a local community, a nation, or of the planet as a whole—illustrates the ecological impact that that population places on nature. EFA identifies the position of each nation as it moves along the pathway towards sustainable development. They draw attention to the inequalities between nations in terms of burdens they place on the Earth's biosphere. This global imbalance was noted by the WWF (Loh & Goldfinger, 2006) for the years between 1975 and 2003, when wealthy nations improved their so-called quality of life by increasing their resource use. Over the same period, some rapidly developing nations—notably China and India—grew significantly, but without raising their per capita footprints (Loh & Goldfinger, 2006). A population may be termed as being in *ecological debt* (Simms, 2005), or deficit, when its consumptive environmental footprint exceeds its own biocapacity. Monfreda *et al.* (2004) noted that this is possible by either importing biocapacity from other nations or by liquidating natural capital. It is thought that as the national

ecological debt grows, there may be a shift in the geopolitical fault line (Loh & Goldfinger, 2006). Instead of having a demarcation between countries on each side of the North–South divide, the line should perhaps be drawn between ecological creditors and debtors.

Potential Determinants of National Environmental Footprints

The national environmental footprints computed for the WWF study (Loh & Goldfinger, 2006) as well as other parameters from international data sets were employed to find the main determinants of humanity's environmental impact. Hammond (2006) in his original study only considered population density, national income, energy intensity, and carbon emissions. Here we consider a much larger array of variables, including not only those previously evaluated by Hammond, but also a wide range of other climatic, geographical, and technological factors. National per capita environmental footprints (ef) were initially postulated to be a function of economic well-being (measured in terms of *Gross National Income* on a 'purchasing power parity' basis; GNI), *population density* (PD), *energy intensity* (EI), *carbon emissions ratio* (CR), *temperature ratio* (Temp R), *precipitation ratio* (PR), *yield ratio* (YR), *technology ratio* (Tech R), *soil fertility* (SF), *terrain* (Terr), *latitude* (L), *fertiliser ratio* (FR) and *irrigation ratio* (IR). These dependent variables were determined via a 'brainstorming' process between the authors. Some factors that the authors would have liked to include in the present analysis, such as biodiversity, were found to be difficult to formulate as a quantitative parameter that could be readily deduced from international databases. Technological innovation in the agricultural sector may obviously lead to increased cereal yields per hectare of land used (by using fertilisers that effect the harvest) and increased yields from livestock (by enhanced feed and heating), although energy resources would be required to achieve this. The availability and use of global cropland area rose by something less than 10% in the period of 1961–1999, despite the population doubling (Environmental Assessment Institute, 2002). In the WWF *Living Planet Report 2002* it was suggested that this was made possible through developments in irrigation, the use of fertilisers, and what was termed 'technological progress' (Loh, 2002). Thus, it is possible that cropland productivity may be able to keep pace with the growing population. If the 'world farmer' were able to reach the average yield of today's US corn grower, then 10 billion people (above the United Nations mean population forecast for 2100) would only need around half of the present cropland, while they would be able to consume today's US calorie intake (Ausabel, 2000). This implies that with advancement in farming methods, such as irrigation and fertiliser use, future cropland area might only require minimal growth. Nevertheless, there is clearly an issue around the disconnect between regions of agricultural production and those regions where humans consume food. These would need to be balanced by developments in food preservation, storage and long-distance transportation.

Climatic factors, such as precipitation and temperature, were considered as potentially significant influences on national environmental footprints. It was thought that the temperature profile across arable land would, for example, have an impact on food productivity. Hot and cold climatic extremes within different regions of the world are likely to result in reduced productivity, as is the case of parts of the Russian Federation. The temperature across habitable areas could also

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influence the energy use of a nation, particularly for space heating or cooling. Northern Europe uses more energy for heating than do warmer climates, like central Africa. However, wealthier countries with large temperature extremes, such as the USA, may also have higher energy use in the summer and winter, than spring and autumn, due to the use of air-conditioning and heating respectively during climate extremes. The rainfall (precipitation) experienced by a nation could be cross-correlated with crop yields. Mean national values for both temperature and precipitation were therefore analysed. Clearly there are inaccuracies in taking averages for larger countries with considerable internal geographic variations. But accurate data sets were not available to discriminate between climatic variations and crop yields within large (sub-continental) nations.

Soil fertility is likely to influence the crop yield of biologically productive land in much the same way as temperature and precipitation. Indeed, humanity is dependent upon soil as a resource for food, fuel and fibre (Swift, 1991). It was difficult to define soil fertility for different nation states from around the world as some areas suffer from deficiencies in certain nutrients, while others are nutrient rich. Soils with a low cation exchange capacity (CEC) have a low inherent fertility, as well as a low capacity to retain nutrients added as fertiliser (Bot *et al.*, 2000). An assessment of the impact of CEC was therefore undertaken. This was based on the amount of a representative crop grown per unit of cropland, or yield. Wheat was chosen as a marker crop, since it is grown in 115 of the 145 nations analysed in the WWF *Living Planet Report 2006* (Loh & Goldfinger, 2006).

Terrain was assumed to be another factor that could affect national environmental footprints. This was difficult to measure, as there are many different types of terrain. In the present study, the assessment of terrain was made in terms 'steep-lands'. The United Nations (1999) in preparing its landmark document associated with its *Agenda 21* programme implied that mountainous regions are at high altitudes and have steep slopes. However, it is not necessarily the case that only steep slopes at high altitudes give rise to problems associated with land slip and soil erosion. Lowland slopes are also vulnerable to these effects; for instance in the East African Rift Valley. Thus, the FAO data for steeplands was utilized here (FAO AGL, 2003). They suggest that 'steeplands' are the class of terrain that has dominant slopes of greater than 30% incline.

The Correlation Equation and Potential Dependencies

Per capita environmental footprints (ef)—in global hectares (gha)—can be represented as a function of various independent variables (or determinants) in the form of a 'power-law' correlating equation:

$$ef = \text{constant}\{(GNI)^a(PD)^b(EI)^c(CR)^d(TempR)^e(PR)^f(YR)^g(TechR)^h(SF)^i(Terr)^j(L)^k \\ \times (FR)^l(IR)^m\}$$

Scaling of this type is a common approach used in engineering and the thermal sciences (Duncan, 1953; Kline, 1986). Such expressions reflect the relationship between size and rank in a sample, represented by an equation in which the independent variables are raised to powers (Hammond, 2006). This has been shown to be a robust method traditionally employed to correlate experimental data, for example, heat transfer phenomena that are often underpinned by rate equations.

The 'constant' in the above power-law correlation effectively includes a unit converter that ensures that the equation satisfies the so-called 'principle of homogeneity of dimensions' (see, for instance, Hammond, 2006). In order to determine the empirical coefficients (both the constant and the exponents) in this correlation equation, a range of international statistics were utilised for the year 2003. The same data sources were adopted, when appropriate, as those utilised by Hammond (2006) in order to ensure comparability:

- Per capita GNI in international dollars from the World Bank's *World Development Indicators 2005* (World Bank, 2005)
- Population size in millions and land area in km² was sourced from the WWF (Loh & Goldfinger, 2006)
- Primary energy use in EJ from World Bank's *World Development Indicators 2005* (World Bank, 2005)
- Carbon dioxide (CO₂) emissions in Mt from the Carbon Dioxide Information Analysis Center (Marland *et al.*, 2007)
- Average national temperatures in °C from the Tyndall Centre for Climate Change Research (Mitchell, 2003)
- Average national precipitation in mm from the Tyndall Centre for Climate Change Research (Mitchell, 2003)
- Wheat yield in hg/ha (FAOSTAT, 2007)
- Level of technological advancement was measured by the number of fixed lines and mobile telephones per thousand in a nation (World Bank, 2007)
- Soil fertility in terms of low CEC, in cmol/kg, and with associated major constraints (FAO AGL, 2003)
- Terrain in terms of steeplands in km² (FAO AGL, 2003)
- Latitude in degrees from the equator (CIA, 2007)

The use of so many variables was thought inappropriate given the inaccuracy within international data sets for several of the parameters. Moreover, correlation of this sort requires the variables to be independent of each other, and that the per capita environmental footprint should ideally be strongly dependent on specific factors. It was anticipated that some of the above variables would be dependent on each other, that is cross-correlated. Multi-linear regression was therefore employed to ensure the analysis was cross-examined for the suitability of the correlation. Such a regression technique presumes that there is only one dependent parameter (in the case of this study, for the environmental footprint (ef)), which is influenced by several independent variables (for example, GNI). The total number of nations evaluated here was reduced to 109, due to the limited availability of some data in international statistical data sets. This is still a good representation of the world community of nations. The countries that were omitted were generally from the class of nations with low income, where statistical sources are scarce and often inaccurate (see also Hammond, 2006).

Evaluating the Power-Law Empirical Coefficients

Power-law correlation provides a means for assessing the significance of each independent variable in respect to national environmental footprints. Each parameter was initially plotted against the per capita environmental footprints in order to determine the strongest power-law dependency. The remaining variables were then plotted against this combination in order to find additional

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dependencies. Many of the parameters were eliminated from the ‘power-law’ correlating equation in this way due to their cross-correlation with the more influential determinants, usually GNI, or because they have negligible influence on ef. When the values for all the exponents were substituted into the original ef expression, a reduced-form ‘power-law’ correlation was obtained:

$$ef = 0.0093 \times GNI^{2/3} \times PD^{-1/10}$$

This equation demonstrates that the environmental footprint is heavily dependent upon national income and weakly so on population density (Figure 3), in a manner similar to that previously found by Hammond (2006). Note that this and the following figures are presented in terms of logarithmic scales. Thus, the differences between the highest and lowest values on the graph are several orders of magnitude (i.e. factors of 10) apart.) However, the dependency of population density is significantly weaker than that found earlier: the exponent b was found to be $-1/10$ as opposed to $-1/4$. Hammond’s study was based upon 1999–2000 data, while the present study utilised more recent 2003 data, and so some differences were expected. The statistical trend line for the present data displayed a very weak negative correlation, although the R^2 value (which was close to zero) indicated that the data fit was relationship poor. None of the wide range of new parameters tested here was found to significantly affect per capita national environmental footprints: the yield ratio, temperature ratio, precipitation ratio, soil fertility, terrain, and latitude. The scatter of data amounts to an uncertainty interval in ef equivalent to a standard deviation of some 100% (see, e.g. Figure 3). This would appear large to a physical scientist, but is in keeping with the scatter inherent in many data sets related to human affairs found in the domain of social scientists (Hammond, 2006). There are various factors that cause the broad spread of correlated data, such as the uncertainty associated with international data sets and the relatively poor quality data for some developing countries.

The constant in the above ‘power-law’ correlation effectively includes a unit converter that ensures that the equation satisfies the so-called principle of homogeneity of dimensions (Duncan, 1953). Correlation yielded $c \sim d \sim 0$, which implied that per capita primary energy consumption (for 2003 data) and

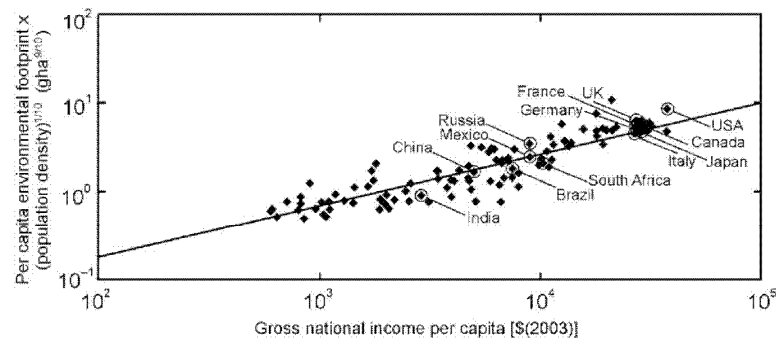


Figure 3. The dependence of per capita national environmental footprints on per capita national income and population density.

associated carbon emissions were directly proportional to national income. These parameters were therefore eliminated from the 'power-law' equation as they displayed a close dependence upon national economic welfare. To include them in the correlation would amount to double accounting for the effects of economic well-being. The rapidly developing countries, such as China and India, are among the largest consumers of total primary energy (Figure 4) and, correspondingly, total CO₂ emissions in the world (Figure 5). However, India and the PRC are below the international mean in terms of energy intensity (measured in units of energy per GNI; MJ/\$ (2003); see Figure 6), although they have above average carbon ratios (micrograms of carbon per unit of energy; $\mu\text{g C/J}$; see Figure 7). Energy intensities can be seen to decrease with national income, a trend that would be required to continue in order to steer nations towards sustainable development.

The technology, agricultural and yield ratios were again found to be directly proportional to per capita national income, and were thus removed from the 'power-law' equation (see, e.g. Figure 8). Improved crop yields were the result of better irrigation, the use of fertilisers, and technical progress generally. This was in agreement with the findings that precipitation, temperature, terrain, soil fertility, and indeed latitude make little difference to the overall yield ratio and consequently to per capita national environmental footprints. It was found that yield was a function of technology, irrigation, and fertiliser, with technology having the dominant effect. However, these three factors were all themselves strongly linked to economic prosperity, characterized by per capita GNI. The overriding factor influencing yield was therefore economic well-being, which

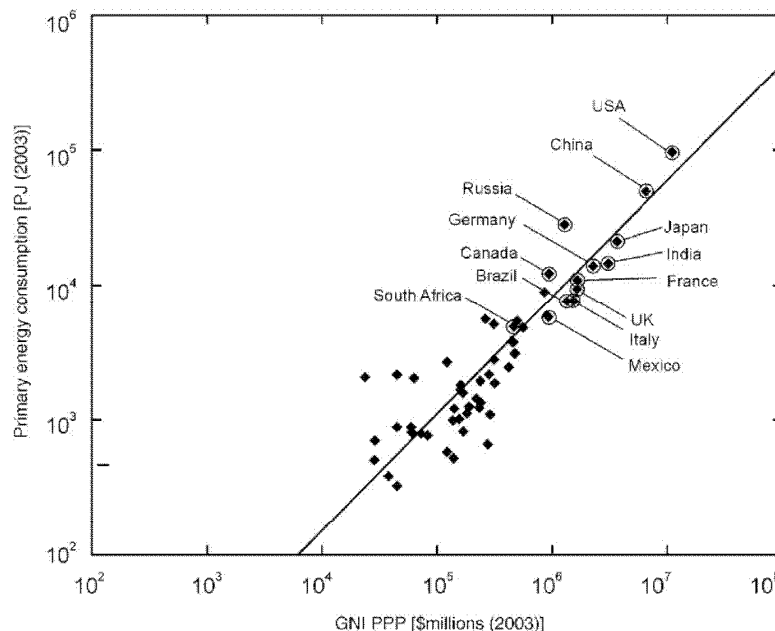


Figure 4. The primary energy consumption of nation states from around the world. GNI is expressed in purchasing power parity (PPP) dollars.

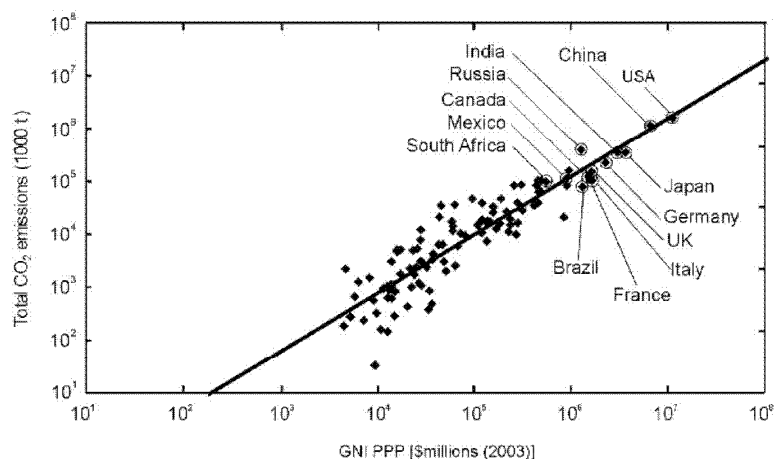
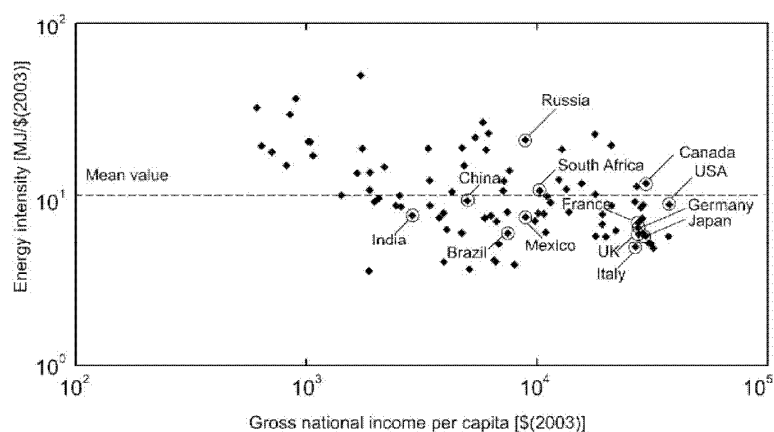
132 *G.R. Cranston et al.*Figure 5. Total annual CO₂ emissions for countries around the world.

Figure 6. The energy intensities of nation states around the world.

itself drives technological progress (Figure 8). Developed or industrialized countries (including the UK, France, and Japan), which have high levels of national income, follow a trend towards exhibiting ever greater agricultural yield ratios over the recent past.

North–South: The Implications of National Footprints

Human Appropriation of Natural Capital

Developed nations (including the G8 countries) tend to be more services orientated, and are therefore less energy intensive than the developing countries, where heavy industry is sometimes a dominant force in the economy. The

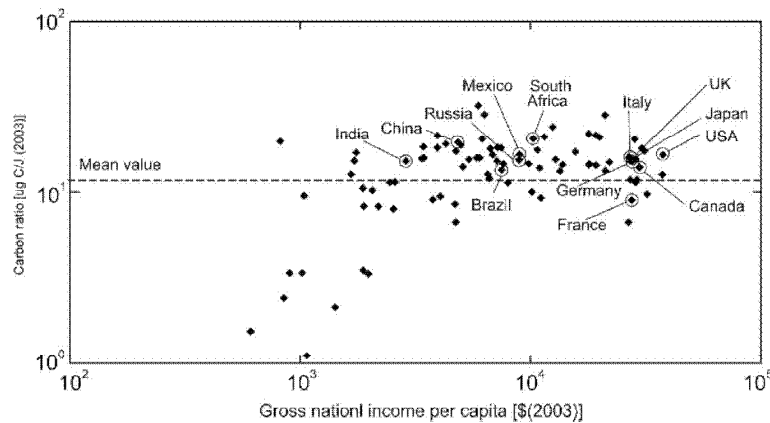


Figure 7. The carbon ratios associated with individual countries from across the world.

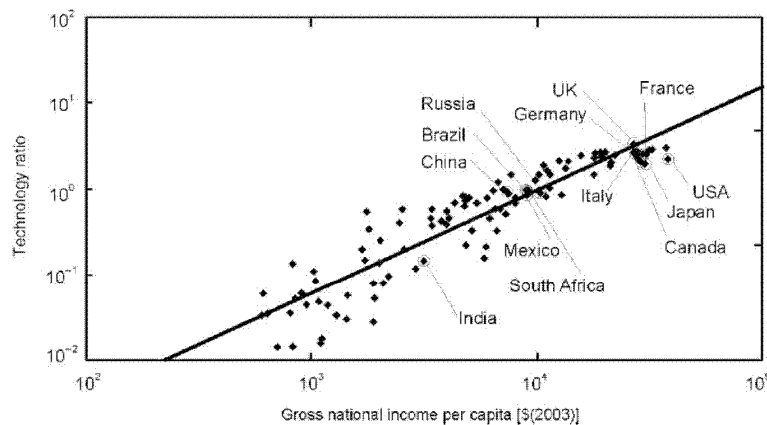


Figure 8. The dependence of the technology ratio for nation states of the world.

exception was found to be the Russian Federation, which had a notably high value for its energy intensity (Figure 6), implying a wasteful use of energy. This may stem from the relative inefficiency of heavy industries under the pre-1990 Communist regime that was a result of a economic strategy of rapid industrialisation (Hammond, 2006). The USA has an energy intensity close to the international mean value (Figure 6). Other G8 industrialized nations, including those from the European Union (France, Germany, Italy, and the UK), and Japan have energy intensities significantly below this to the mean in 2003. Here primary energy is restricted to commercially traded sources only. Non-commercial fuels, such as animal wastes, peat and wood, play an important role in many developing countries, but they are poorly recorded in national energy statistics. Goldemberg (1996) estimates that such non-commercial sources contribute around 23% of the total energy consumed in the 'Majority South'—the African, Asian and Latin American regions of the world. Fossil fuel consumption typically accounts for

between some 33% and 60% of national environmental footprints for low-income and high-income countries, respectively (Hammond, 2006). Emerging countries like China and South Africa have energy intensities also close to the international mean value (see again Figure 6). In contrast, Brazil, India and Mexico have values similar to those of the EU G8 nations. The carbon ratio, on the other hand, generally reflects the extent to which nations are dependent on particular types of energy resource—principally coal, oil, natural gas, and nuclear power. The latter, together with ‘renewable’ energy technologies, provide a near-zero carbon resource. National carbon ratios (Figure 7) are even more closely clustered around the global mean value than are the energy intensities, with just a few low-value outliers—such as developing countries (not part of the G8 + 5 grouping) that principally draws carbon-free hydropower. China and India, along with other developing countries, are more dependent on ‘dirty’ fuels like wood and coal, resulting in their relatively high carbon ratios. Developed nations should clearly be more carbon efficient because of their advanced technology. But the actual amount of carbon released per Joule does not vary greatly with per capita national income (see again Figure 7). Industrialized G8 countries tend to use oil, natural gas, and nuclear power. France’s relatively low carbon ratio can be attributed to the many nuclear power stations that supply the country with the bulk of its electricity.

The inclusion of population density in the ‘power–law’ correlation (Figure 3) allows for an assessment to be made of whether countries with a similar combination of income and population density have comparable scaled environmental footprint. Their position, in relation to the ‘power–law’ data correlation, implies that given countries have footprints *typical* (that is, close to the ‘mean’ value) of nation states with a similar combination of income and population density. The relative position therefore indicates whether specific nations are profligate or frugal in terms of the use of natural capital. Those located above the ‘power–law’ correlation curve are wasteful, while those below it are more careful in terms of their resource use (Figure 3). The European G8 countries and Japan were clustered together on these curves (Figure 3), while the Russian Federation and the USA are seen to have per capita environmental footprints just above the correlation equation. The emerging economies, such as China, India, and South Africa, were evidently more sparing in their use of natural capital on this basis. Nation states that are placed above and below the curve are distributed across the spectrum of socio-economic groups; national consumption patterns of biophysical resources do not appear to be related to wealth or poverty per se.

Ecological Debt and Overshoot

It has been shown that nation states import resources from beyond their borders and likewise export materials, goods and services. They are rarely in trade balance. In addition, pollutant emissions and wastes can have an impact on a local, regional, and international scale. The environmental consequences of such cross-border flows can be presented in terms of a country’s *ecological debt* with other nations: the difference between its environmental footprint and its ‘biocapacity’ (see Potential Determinants of National Environmental Footprints for a related discussion of the environmental consequences of trade between importing and exporting countries). This is because, if the environmental footprint is analogous to individual ‘spending’, then the biocapacity would reflect their ‘credit

limit'. It has been found that, in general, this ecological debt is owed by the industrialized countries of the North to the developing nations of the populous South (Simms, 2005). A closely related parameter is the overshoot ratio (OR) defined as (Hammond, 2006)

$$\text{OR} = \text{national environmental footprint} / \text{biocapacity}$$

Those countries that owe an ecological debt to other nations or regions will exhibit an OR greater than unity ($\text{OR} = 1$), and visa versa. Many of the individual countries shown in Figure 9 display an OR greater than unity. The European Union (EU-27) has a mean value of $\text{OR} = 2.18$ (based on 2003 data; Loh & Goldfinger, 2006) with the EU G8 members having values of 1.87 (France), 2.65 (Germany), 4.20 (Italy), and 3.50 (UK). They all owe an ecological debt to those regions of the world (principally in the South) from which they import resources and deposit emissions and waste products. The remainder G8 nations have overshoot values of 0.52 (Canada), 6.29 (Japan), 0.64 (the Russian Federation), and 2.04 (the USA) (see also the graphical presentation of 2000 data by Hammond, 2006). Only the sparsely populated countries of Brazil, Canada and Russia display an ecological under-shoot and are therefore currently in ecological credit. The five large emerging economies (illustrated in Figure 1) have ORs of 0.21 (Brazil), 2.00 (China), 2.00 (India), 1.53 (Mexico), and 1.15 (South Africa). In 2003, the average overshoot of the planet as a whole was 1.78; enabled by the use of fossil fuels laid down over geological timescales. Thus, although Brazil is in significant ecological credit with the rest of the world, the other emerging economies are roughly in line with the planetary mean, which overshoot its footprint by some 80% in 2003. Many poor developing countries in Africa, Asia, and Latin America, not highlighted here, are in ecological credit (see, e.g. Hammond, 2006). In 1965 the mean global overshoot was only 0.59, rising to 0.82 in 1975, 0.97 in 1985, and 1.12 in 1995. There are relatively large uncertainties associated with the calculation of footprints and biocapacities (Doughty & Hammond, 2004; Eaton *et al.*, 2007). But it appears that the human appropriation of natural capital exceeded that available on the planet around the end of the 1980s. There is clearly a need

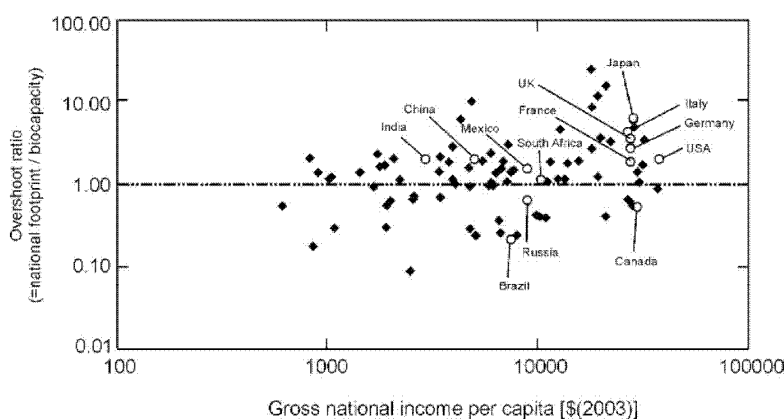


Figure 9. Biocapacity overshoot or undershoot of nations from around the world.

over the long term to bring the Earth's environmental footprint back into balance with its biocapacity.

A comparison with the 'Earthshare' (1.80 gha in 2003 (Loh & Goldfinger, 2006)) indicates how close humanity is to achieving 'One Planet Living' (Eaton *et al.*, 2007). That would require a rate of consumption of natural resources equivalent to 1.8 gha per person. If the rest of the world consumed as much as is currently done to achieve UK 'standard of living' then the resources of three planets would be required, following USA trends six planets would be necessary, and for the United Arab Emirates (UAE) 10 planets. However, it must be borne in mind that this notion of an 'Earthshare' is simply an ethical construct (Eaton *et al.*, 2007)—a value judgement about fair national shares in environmental impacts. In practice, it is unlikely, given the disparity in global wealth and resources between the prosperous 'North' and 'Majority South', that the different nations of the world will converge towards 'One Planet Living' during the twenty-first century. This would need, for example, a major reduction in energy demand, along with a shift from a dependence on fossil fuel and uranium resources (so-called 'capital' energy sources) to renewable energy technologies (mainly solar-driven, 'income' sources) in both the industrialized and developing nations. Only then would humanity be able to secure a low carbon global economy.

Carbon Emissions and Global Warming

The 'energy land' category of the environmental footprints (see Figure 2) reflects the area required for new forests (anywhere in the world) needed to absorb CO₂, and thereby stabilize the atmosphere. (It has been suggested that this influential, often dominant, land type could alternatively be calculated from the area required to replace fossil fuels with wood biomass (Chambers *et al.*, 2000).) Per capita carbon emissions are closely associated with economic wealth, and hence with the United Nations Development Programme ranking according to their Human Development Index. Industrialized countries, particularly the USA, emit a large fraction of total greenhouse gases (GHGs; see the corresponding annual total CO₂ emissions shown in Figure 5), and might be required to significantly curtail their carbon emissions in any future climate change mitigation regime that might succeed the Kyoto Protocol. The UK government, for example, has committed itself to reducing CO₂ emissions by 80% by 2050 against a 1990 baseline. On that timeline, many of the other environmental effects that contribute to global and national footprints will have come to the fore. In the transitional pathway towards a low carbon future in 2050, CO₂ quotas for the developed countries would need to fall, while those of poorer developing nations would perhaps be permitted to rise with economic wealth and (hopefully) well-being, thereby removing 'grandparent emissions' (cumulative or historic national emissions). Insights derived from environmental footprinting discussed here, such as the need for humanity (and, more debatably, individual countries) to live within biocapacity constraints, may aid the post-Kyoto negotiations that will ultimately need to take place amongst all the major nations and geo-economic groupings on the planet (Hammond, 2006). They may put into perspective the future GHG burden-sharing arrangements between the wealthy nations of the northern hemisphere and the 'Majority South'.

There are ongoing negotiations within the ambit of the UN Framework Convention on Climate Change over the successor regime to the Kyoto Protocol.

At the time of writing (late 2009), the major players have indicated what they might contribute to CO₂ mitigation in the medium term. The European Union, which emitted 4721 Mt of CO₂ in 2006 (10.22 t per person; US EIA, 2009), formally negotiates on behalf of its members. It has suggested that it will cut emissions by 20% on 1990 levels by 2020, although with the possibility of increasing this target to 30% should a new climate deal be agreed internationally. The USA is the largest emitter of carbon worldwide (Figure 5): 5903 Mt of CO₂ in 2006 (19.78 t per person). However, the Obama administration has only committed itself (subject to the approval of Congress) to return its emissions to 1990 levels by 2020. The Russian Federation emitted 1704 Mt of CO₂ (12.00 t per person), and has set an emissions target of a 10–15% cut by 2020 compared with 1990 levels. The new Japanese Prime Minister Yukio Hatoyama announced a 25% cut in GHG emissions by 2020 on 1990 levels in September 2009. Japan emitted 1247 Mt of CO₂ in 2006 (9.78 t per person). The PRC emitted 6018 Mt of CO₂ in 2006 (4.58 t per person). China will not reduce overall annual emissions, but is committed to establishing a 'carbon intensity' target. They have also pledged to use 15% of renewable energy sources by 2020, and plant 40 million hectares of new forest as a carbon sequestration measure. India (that emitted 1293 Mt of CO₂ in 2006 (1.16 t per person)) has indicated that it will resist any attempts to impose binding caps on it. Their government believes that the industrialized countries should take responsibility for carbon mitigation. Nevertheless, India has suggested that it might take 'aggressive' voluntary action to combat climate change.

CO₂ released into the atmosphere from the burning of fossil fuels is thought to persist for (or have a residence time of) around a hundred years. The build-up of atmospheric CO₂ concentrations is therefore largely a consequence of emissions released by the countries of the 'North' since the start of their so-called industrial revolution around the turn of the nineteenth century. Thus, the USA has emitted about 314,772 Mt of CO₂ over the period of 1900–2004 (US EIA, 2009). Historic emissions from the EU during the same timescale amounted to 273,221 Mt, while that of Russia and Japan totalled 89,688 Mt and 42,696 Mt, respectively. This can be contrasted with the cumulative emissions from China and India of 89,243 Mt and 25,054 Mt, respectively. It can consequently be argued, on equity grounds, that the industrialized nations should take the lead in mitigating the global release of GHGs because they are principally responsible for their lifetime concentrations.

Concluding Remarks

The role of environmental footprinting has not gone without challenge. The uncertainties and deficiencies of using footprints (and related parameters) include problems associated with boundary definitions, data gathering, and the basis for weighing the various consumption and associated impacts (Doughty & Hammond, 2004; Eaton *et al.*, 2007). Its adoption as a tool for decision-making in a policy context depends on an understanding of these assumptions and uncertainties. The global and national footprint results periodically reported in the WWF *Living Planet Report* (Loh & Goldfinger, 2006) have been viewed by some (see the discussion in Hammond, 2006) as amounting to something of a 'doomsday' scenario in the tradition of Thomas Malthus' population projections in the nineteenth century and the classic *Limits to Growth* study in 1970s. Criticisms have also been made concerning the dominant influence of fossil fuels in footprint

calculations. It may underestimate the potential of a switch to renewable energy technologies in lowering the planetary footprint (Hammond, 2006). Indeed 'technological optimists' typically argue that new technology will enable humanity to overcome biophysical limits (Costanza, 2000), thereby making development sustainable. Recently, McManus and Haughton (2006) have offered what they term a 'sympathetic critique' of both the theory and practice of environmental footprinting. They believe that, if poorly interpreted, it can mislead policy makers. Users should therefore be aware of its strengths and weaknesses, like those noted here. But even McManus and Haughton acknowledge that it has great 'visual and commonsense appeal'.

Environmental footprints are important, albeit partial, aggregate indicators of a nations' progress along the sustainable development pathway. The correlation of national footprints reported here indicates the extent to which various nations degrade natural capital in generating their national income (Figure 3). It has been shown, in common with the earlier study by Hammond (2006), that per capita national environmental footprints were strongly dependent on economic prosperity, but only weakly on population density. Small variations were found in empirical coefficients linking income and population density to the footprint in comparison with the original study. Other determinants analysed in the present research were found to be, by and large, proportional to per capita national income. They were eliminated from the correlation process in order to avoid double accounting (the exponents in the 'power-law' correlating equation were set equal to zero). The final 'power-law' correlating equation was used to highlight the situation in the G8 + 5 nations. Developing countries were found to have higher energy intensities, but with lower carbon ratios. This was contrasted with developed nations which, despite having lower energy intensities, tend to have higher than average carbon ratios. This implies that the advanced technologies available in the developed world were not leading to a low carbon economy. Greater emphasis will need to be placed on the adoption of low or zero carbon technologies, such as energy efficiency measures, nuclear power, or renewable energy systems. The 'power-law' correlating equation indicates which specific countries are relatively profligate or frugal in terms of their use of natural capital.

On a national scale, the environmental footprint can be used to examine the effect that different trading patterns could have on the footprint. In this way, sustainable development strategies can be created and implemented in a way that reflects their importance on the global and local environment. The national and global footprint data published by the WWF in their *Living Planet Report* (Loh & Goldfinger, 2006) highlight the global inequity associated with the acquisition of the world's resources. It illustrates that the richer, more developed countries are the primary cause for the current global ecological debt. It is inevitable that, as the poorer countries aspire to become more industrialized, the vision of a 'better' way of life will result in a larger global footprint, a growing ecological deficit, and a rising OR. A consequence of the rapidly growing world population is the continuing overshoot of available natural resources.

Acknowledgements

This is a revised and updated version of a paper originally presented at the International Ecological Footprint Conference: *'Stepping Up the Pace'* held in Cardiff,

Wales over 8–10 May 2007 (denoted then as paper M94). The contribution by the first author (GRC) has been supported by the University of Bath's Strategic Investment Fund. The second author's research (GPH) on energy, environment, and sustainable development has recently been supported by research awards and contracts in the UK from the Carbon Trust, the Engineering and Physical Sciences Research Council, E.ON UK (the electricity generator), the Great Western Research (GWR) Alliance, and the UK Energy Research Centre. The third author (RCJ) thanks Hampshire County Council and the Higher Education Funding Council for England (HEFCE) for financial support of his studies. The authors are grateful for the care with which Gill Green prepared the figures.

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Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

North and south: Regional footprints on the transition pathway towards a low carbon, global economy

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ARTICLE INFO

Article history:

Received 30 April 2009
 Received in revised form 10 August 2009
 Accepted 14 August 2009
 Available online 8 September 2009

Keywords:

Environmental footprint projections
 Resource use
 Carbon emissions
 International development
 Sustainability

ABSTRACT

Environmental or 'ecological' footprints are indicators of resource consumption and waste absorption transformed on the basis of biologically productive land area required *per capita* with prevailing technology. They represent a partial measure of the extent to which the planet, its regions, or nations are moving along a sustainable development pathway. Such footprints vary between countries at different stages of economic development and varying geographic characteristics. A correlation equation for national environmental footprints is used, alongside international projections of population growth and gross regional income, to estimate the relative contributions of the peoples of the industrialised North and populous South that would be needed in order to secure climate-stabilising carbon reductions out to about 2100. The four so-called 'marker scenarios' produced by the *Intergovernmental Panel on Climate Change* are used to estimate the degree of energy efficiency improvement and carbon mitigation that is feasible. The present footprint projections suggest that a reduction in the consumption of biophysical assets across both the developing and industrialised world is indeed possible. However, the developing world's footprint is shown to overshoot that of the industrialised countries by around 2010–2015. It then levels out and starts to fall, on the most optimistic scenario, by about 2050. In order to achieve global sustainability in the 21st Century a serious commitment to environmental protection is required in both the industrialised North and the 'majority South'. That implies balancing population growth, economic well-being, and environmental impacts in the interests of all the people and wildlife on 'Spaceship Earth'.

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1. Introduction

It is obviously important for developed, or industrialised countries (in the prosperous 'North') to play their full part in maintaining environmental sustainability as they currently emit the bulk of carbon dioxide (CO₂) and other gaseous pollutants into the atmosphere [1]. But sustainable development must also be viewed in a global context. The task facing the nearly 80% of the world population that live in developing countries (the 'majority South') is daunting. The countries that make up these two regions of the world are depicted on the global map shown in Fig. 1. It can be seen there that Australasia (Australia and New Zealand) are 'honorary' member countries of the North. The South has, in most cases, rapidly growing populations that will drive up energy consumption and environmental pollution. This will feedback to the whole planet, and thereby alter the climate experienced by the wealthier nations. Consequently the South needs assistance from these industrial countries in order to promote their economic growth (which will, in time, induce a "demographic transition" [1]) and

to improve the efficiency of their energy systems. Economic development would benefit from, perhaps even require, fairer terms of trade between the OECD and developing countries. Environmental sustainability could be aided by the transfer of best practice energy technologies from the richer to poorer regions. This will ultimately be in the interests of all the citizens of 'Spaceship Earth' [1].

Environmental or 'ecological' footprints have been widely used in recent years as indicators of resource consumption and waste absorption transformed on the basis of biologically productive land area required *per capita* with prevailing technology. The concept was developed by Wackernagel and Rees [2] as a simple, yet graphic measure of humanity's impact on the environment. These footprints represent a partial measure of the extent to which the planet, its regions, or nations are moving along a sustainable development pathway. The footprint of a nation is defined by the amount of land and water its population utilises; for food, materials, built-up areas, waste assimilation and the like. Footprints are spatial indicators, measured in global hectares¹. Such footprints

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¹ A global hectare represents a standardised average productive hectare. Equivalence and yield factors are used to convert from hectares to global hectares, to ensure uniformity across differing regions.

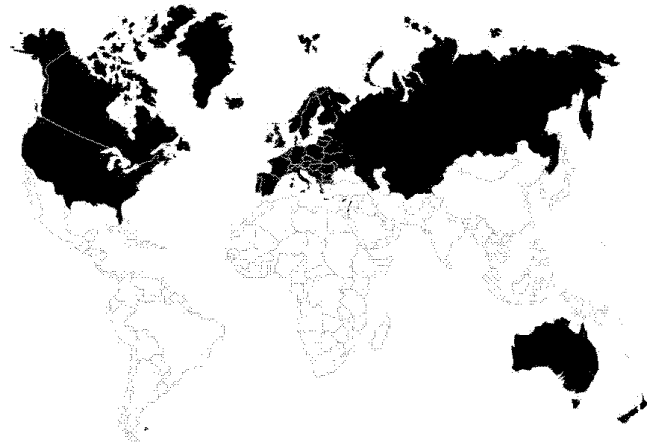


Fig. 1. The global north-south divide [The industrialised 'North' - black; the populous or majority 'South' - white with black edging].

vary between countries and regions at different stages of economic development and varying geographic characteristics. The determinants of these footprints have recently been correlated in terms of the economic wealth and population densities of countries from around the world [3,4].

The temporal trajectories for environmental footprints indicate the sort of pathways that are required to protect the biosphere, and can be implemented as a resource accounting tool that is often used to address underlying sustainability issues [5]. As well as being a simple measurement, it can be used to illustrate the extent to which humanity is using nature's resources faster than they can regenerate. These footprints draw attention to the inequalities between nations in terms of burdens they place on the Earth's carrying capacity. Measuring the ecological footprint of a particular population – be it an individual, a city, a nation or all of humanity – allows the assessment of the extent to which its biocapacity is overshoot. Humanity's footprint is currently over 23% larger than that which the planet itself can regenerate [5]. The population is living on resources (principally fossil fuels) laid down over geological timescales. Many high consumption regions are far from self-sustaining, and they only exist by drawing upon the resources from beyond their borders [6]. Industrialised countries (of the prosperous 'North') exhibit huge *per capita* ecological footprints, while the economically-disadvantaged nations (of the majority 'South') currently have relatively small environmental footprints. A key element of the sustainable development is therefore the need to focus on greatly improving the efficiency of resource use, and on reducing carbon (and other pollutant) emissions. Such actions would lower the environmental footprint of differing countries or regions of the world, and move humanity towards 'sustainability'.

The distinguished systems ecologist Odum, and his wife Elizabeth (see, for example Odum and Odum [7] and Hammond [8]), argued that the industrialised nations would have to descend from their current profligate growth path. They suggested that civilisations rise, before their subsequent decline and fall; an idea that Odum took from 'Nature's Pulsing Paradigm'. His long association with ecosystem science predisposed him to a cycle of growth, climax, descent, and low energy restoration. The Roman Empire in Europe (270 BC–AD 476) and the Mayan civilisation of Mesoamerica (AD 300–900) are classic examples of the decline of human societies according to Hammond [8]. In the modern era, the decline would be marked by the end of the predominance of cheap oil; long predicted by King Hubbert and others [8]. It is unlikely that

humanity will ever again have access to concentrated energy sources of the nature of the fossil fuels: coal, natural gas, and oil. Resource scarcity and consequent rising costs will, according to the Odums [7], induce the global economy to contract. Whether or not humanity will experience a collapse (with or without the Odums' "prosperous way down" [7]), or will be able to secure a sustainable future for people and wildlife, it is too soon to tell [8]. Equity arguments will persist about whether burden sharing should be made on a *per capita* basis, on the available biocapacity of developed and developing regions, or account should be taken of their relative economic wealth. Nevertheless, both footprint analysis and systems ecology yield tools for coupling economy and ecology, along the lines advocated in the influential Brundtland report [9]. They also provide a means for raising awareness of global sustainability issues amongst the wider populous. Hammond [8] noted that the sort of global footprint analysis undertaken in the present work provide an alternative perspective on sustainability to that of Odum's pulsing paradigm from the natural world.

The environmental footprint is traditionally used to give a 'snapshot' of a population's demands upon nature for a specific year. However making projections of total global and regional footprints into the future, alongside other development indices (like population and economic well-being) is less straightforward. Hammond [3] developed a correlating equation that relates the *per capita* environmental footprint of nation states to their population density and economic wealth. This expression was subsequently revised by Cranston et al. [4], based on more recent data and a wider range of independent variables. Like Hammond, they found that the *per capita* footprint of nations is strongly dependent on 'Gross National Income' (GNI) and only weakly on population density (PD), although the coefficients they found were slightly different. The latter equation has been employed in the present work, together with international projections of population growth and of gross regional income, in order to estimate the relative size of footprints for the industrialised North and the populous South up to 2100.

2. Long-term scenarios: a look into the future

2.1. Scenario analysis

The task of anticipating future developments is difficult especially when considering an extremely long time period. Neverthe-

less, long-term scenarios have been developed for the 'visioning' of global energy trends and strategies in the context of climate change science. There is a vast literature on scenario formulation covering narrative descriptions of transition pathways, quantitative scenarios, and detailed models. Scenarios are frequently used in the private sector (most notably by the oil major Shell) and by bodies such as the *Intergovernmental Panel on Climate Change* (IPCC), who focus on the impact of greenhouse gas (GHG) emissions, principally CO₂. These facilitate an analysis of the way in which future global developments will influence the concentration of GHGs in the atmosphere, and their possible impact on climate change. Scenarios of the latter type fall into two categories: those that consider the uncertainties in the drivers for emissions (such as population, economic wealth and technology), or those that analyse uncertainty in the levels of commitment and effectiveness of global efforts to reduce climate change. The scenarios utilised in the present work focus on the driver uncertainties [10].

Scenarios are developed to evaluate future changes in systems that are unpredictable, lack understanding, or involve large scientific uncertainties. It is for these reasons that emissions scenarios have been formulated. There is a significant uncertainty surrounding climate change; in particular the way in which anthropogenic emissions may influence the atmospheric conditions. With so many unknowns, a varied selection of different scenarios have been developed [10]. These scenarios are not predictions or forecasts, but are a suggestion of future alternatives. They are typically formulated using a set of reproducible assumptions based upon historical trends, relationships, and driving forces. Scenarios range in complexity depending on their 'storylines', and consider a variety of plausible possibilities. Thus, a selection of future emissions from low to high can be assessed with respect to future response strategies.

2.2. Four pathways to 2100

The IPCC developed a large variety of scenarios for assessing the different pathways that GHG emissions might follow up to the year 2100. The scenarios are documented in the IPCC *Special Report on Emissions Scenarios* (SRES) [11]. There are four main themes, or 'storylines', that enable different scenarios to be grouped together. Storylines follow different economic, social, environmental, demographic, and technological interpretations; a scenario is a development from a given baseline. In total the IPCC developed some 40 scenarios [11]. None of these were highlighted as being the 'best' or 'worst' case, but were all considered equal and illustrative of different storylines. Despite this, a 'marker' scenario for each group was selected, based upon those that the working groups thought to best reflect each storyline. The marker scenarios have undergone the highest level of assessment and scrutiny by the SRES writing teams in an open process. For this reason many researchers focus on the four markers in their work; see, for example, van Vuuren and O'Neill [12]. These marker scenarios have therefore been adopted here.

The four SRES marker storylines [11] are each characterised by different patterns in population growth, economic welfare and global emissions. They each follow a different pathway into the future. The scenarios and storylines vary significantly; they range from high to low global populations, as well as rapid economic growth and technological development to conservative environmental strategies. The four marker storylines were labelled as A1, B1, A2 and B2. The A1 scenario presumes convergent economic development between regions, an ultimately decreasing world population (by 2100), and abundant energy and mineral resources (due to rapid technological progress). This scenario is driven by the internationalisation of people, technologies and ideas, and a commitment to market-based solutions. The A2 scenario assumes more self-reli-

ance in terms of resources, and there is less economic, social and cultural interaction between regions than is associated with A1. Economic growth in the A2 scenario is more uneven with little inter-regional convergence. The B1 scenario assumes a high level of environmental and social consciousness, with a global strategy focused on sustainable development. A balanced economic development is presumed, with any financial gains being invested into areas such as environmental protection and improving resource efficiency. Finally, the B2 scenario has a similar storyline to that of A2, but with more focus upon climate change mitigation, which is addressed through local community-based solutions.

In order to establish trajectories for global and regional environmental footprints in the current study, scenarios for population and economic wealth were required up to the year 2100. The IPCC scenarios were chosen as the most comprehensive set of pathways over this time period. They have been utilised by many other researchers (such as Grubler et al. [13]), although their limitations and inconsistencies were acknowledged.

3. Global futures and their limitations

3.1. The limits to scenarios

The scenarios developed for the IPCC SRES report [11] might be viewed as rather dated, because they utilise early datasets [12]. New forecasts are necessary to ensure that the most recent data and their forward projection are employed, old thinking is challenged, and better estimates of uncertainties utilised. The population trajectories were the main area where recent forecasts have been made that differ significantly from those used in connection with the SRES projections. There have consequently been many comparisons of new population trajectories with those associated with the original SRES scenarios; see, for example [10,15–17].

It has been recognised by a number of researchers that the SRES scenarios assume too rapid economic growth, and that population trends are unlikely to be so high. Indeed it has been noted that in the long-term between two and four billion fewer people are expected to inhabit the planet by 2100 across the range of predictions [14]. Interestingly, when studies have incorporated the new, more conservative, population projections, the changes in other drivers (such as economic growth) result in little change to overall GHG emissions [18]. The IPCC have themselves stated that, although population scenarios from major demographic institutions are lower than they were at the time of the SRES, they have not been fully implemented in the GHG emission projections found in the recent literature [19]. However, van Vuuren and O'Neill [12] consider that there is no real reason to initiate a complete update of the SRES scenarios, since they regard the inconsistencies in global trends as being relatively small. But they recognised that scenarios do have a limited 'shelf life', and that the data upon which they are based clearly becomes outdated over time. The appropriateness of the population and GNP projections used by the IPCC was therefore re-examined in the present study.

3.2. Inconsistencies in population projections

The population data used in the SRES study has caused some controversy amongst researchers. Nakicenovic et al. [14] assessed various scenarios and projections made after 2001, and compared them with the IPCC SRES and Third Assessment Report (TAR) scenarios. They found that population projections varied significantly. Indeed population was highlighted as being the major driver that needed to be revised, because major reductions in total global populations were likely by 2100 compared to earlier estimates. In order to determine whether the SRES scenarios were appropriate for

the current study, the population trajectories for each marker storyline were compared with the latest data available from the *International Institute for Advanced Systems Analysis* (IIASA) [20,21] and the *United Nations* (UN) [22]. The most recent IIASA data (for 2007 at the time of writing) is significantly different to that available in 2001. There are similar discrepancies in comparison to the UN data (for 2004), although with a much smaller range and far lower maximum population estimated for 2100. However, the medium value for projected population size is consistent with the other data sets (see Fig. 2).

It became evident, from comparing the latest population projections with those obtained using the original SRES marker scenarios that the A2 scenario was out of the range suggested by the latest predictions from the IIASA and UN (see Fig. 2 below). Indeed, even the updated 'A2r' case provided by Riahi et al. [23] was above the range of the 2007 IIASA estimates. The B1 and B2 scenarios for population, on the other hand, display good agreement with recent demographic projections from both the IIASA and the UN.

3.3. Variations in long-term economic growth forecasts

Nakicenovic et al. [14] determined that the economic development estimates haven't varied significantly between the old and new literature; the medians and percentile distributions were essentially the same. Unlike the population trajectories, there are no official organisations that make global economic growth projections into the long-term future. Therefore the only information available is sourced from researchers in the field of climate change studies, who generate scenarios and corresponding projections as part of their work. In order to determine the applicability of the SRES economic growth projections, the marker scenarios were compared with two other academic sources [23,24]; see Fig. 3 below. Both Riahi et al. [23] and Weyant and de la Chesnaye [24] consider economic growth to be the most important determinant of future emissions. Fig. 3 suggests that the SRES economic growth projections are still within the bounds of these more recent estimates; A1 is the only projection that is significantly out of line. van Vuuren and O'Neill [12] suggested that this may be because the A1 marker scenario represents a very high growth rate for the Africa and Latin America (ALM) region. A1 and B1 are both above the mean values suggested by Weyant and de la Chesnaye, whereas A2 and B2 fall below their trends. A2 has a slightly unusual pattern, as it exhibits a low economic growth, but rapid pop-

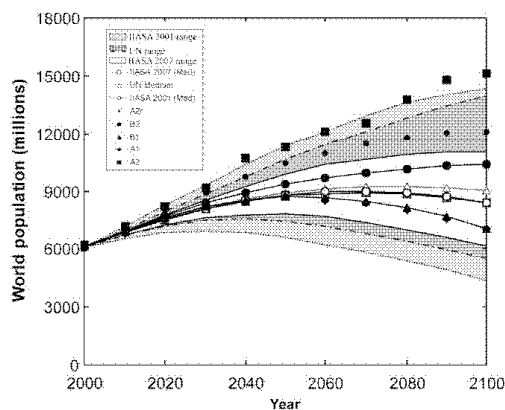


Fig. 2. World population projections.

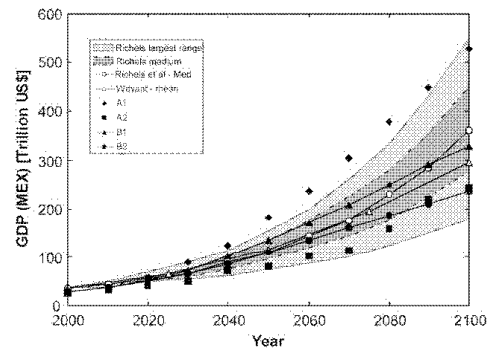


Fig. 3. World GDP projections – SRES markers and updated scenario.

ulation growth. However, up to about 2070 it seems representative of low economic growth forecasts. The SRES projections were found to be consistent with recent economic growth scenarios (see Fig. 3); fitting within the appropriate range forecasts.

A debate has surrounded the way in which the income projections of the IPCC were expressed in terms of *Market Exchange Rates* (MEX), rather than *Purchasing Power Parity* (PPP) [3]. Its working group [25] considered that over long time periods the values for economic growth in terms of MEX and PPP tend to converge for less developed regions. Studies have shown that the choice of exchange rate for GDP does not greatly affect the projected GHG emissions if used consistently [18,19]. Indeed, despite being the most highly debated aspect of the SRES scenarios, the economic growth trends do not vary significantly [19].

4. Environmental footprint projections to 2100

4.1. Bounding the 21st Century

Once the appropriate socio-economic scenarios had been selected, the environmental footprint was calculated for the industrialised and developing world (as depicted in Fig. 1). These were based on the four IPCC marker scenarios, together with recent population projections. The correlating power-law equation of Cranston et al. [4] for national footprints was utilised for this purpose. This shows that the main determinants for the *per capita* environmental footprint up to the early years of the 21st Century were population density and economic wealth:

$$ef = 0.0093 \times GNI^{2/3} \times PD^{-1/10} \quad (1)$$

Here GNI is the equivalent of the 'Gross National Income' for the world or regional populations (in international dollars), and PD is the associated population densities [3,4]. Dimensional analysis and scaling arguments [3], widely used in the engineering and physical sciences, were employed for scaling purposes. The 'constant' in the above power-law correlation [Eq. (1)] effectively includes a unit converter that ensures that the equation satisfies the so-called 'principle of homogeneity of dimensions'. A consolidated dataset of 109 countries was employed to determine the empirical coefficients in Eq. (1) [4]. These ranged widely across the spectrum of nations at different stages of international development from wealthy to relatively poor states. This effectively gave rise to a 'long-run' formulation that can be applied, within the constraints of the present analysis (of the sort indicated in Section 3 above that applies to the SRES scenarios), across the 21st Century.

In order to extend the footprint estimates into the future, it was necessary to adapt this correlating 'power-law' equation to take account of future possible improvements in energy efficiency and carbon reductions. This involved the extension of the above equation [Eq. (1)] to include 'energy intensity' (EI – the primary energy consumption per unit of GNI) and 'carbon ratio' (CR – the carbon emissions per unit of energy consumed) as additional variables [3,4]:

$$ef = K \times \text{GNI}^{2/3} \times \text{PD}^{-1/10} \times \text{EI}^m \times \text{CR}^n \quad (2)$$

The scaling of each SRES marker scenario and associated projections was used to determine a new constant and powers for EI and CR, K , m and n respectively. The final equations were based upon the following parameters:

Scenario	m	n	K
A1	4/3	1/10	0.00022
A2	1	1/2	0.00019
B1	2/3	2	0.000007
B2	1	1/8	0.00056

These represent the asymptotic conditions for each scenario in 2100, whereas the original expression of Cranston et al. [4] was used to represent the pre-2003 trends.

4.2. Modelling the low carbon transition to 2100

The problem of obtaining a correlating equation which will fit between the bounding states (in 2003 and 2100, respectively, here) is one of a class of problems in which solutions are known for asymptotically large and small values of an independent variable, namely:

$$y \rightarrow Ax^p \text{ as } x \rightarrow 0$$

$$y \rightarrow Bx^q \text{ as } x \rightarrow \infty$$

where x and y are the independent and dependent variables, respectively. Fortunately, Churchill and Usagi [26] have developed a general solution for this class of problems in the thermal sciences of the form:

$$y = \{(Ax^p)^m + (Bx^q)^m\}^{1/m} \quad (3)$$

where $m > 0$ if $p < q$, and vice versa. They originally applied this formulation to heat transfer problems involving laminar buoyancy-driven convection, and to laminar, mixed (combined buoyancy-driven and forced) convection. Alamdari and Hammond [27] employed this interpolation formulae to develop improved, full range correlations (across the laminar, transitional and turbulent airflow regimes) for buoyancy-driven convective heat transfer from the internal surfaces of naturally-ventilated buildings. In a similar way, Hammond [28] subsequently utilised this formula to devise a similar expression for calculating the buoyancy-driven convective heat transfer in high-aspect-ratio cavities formed within advanced glazing systems.

The Churchill–Usagi interpolation formula [26] can also be used to yield a smooth transition between the two bounding or end states in the present case. Combining the asymptotic formulae for the *per capita* environmental footprint in 2003 and 2100 [Eqs. (1) and (2), respectively], together with Churchill–Usagi interpolation formula, yields:

$$ef = \text{GNI}^{2/3} \text{PD}^{-1/10} [(0.0093)^{-P} + (K \cdot \text{EI}^m \text{CR}^n)^{-P}]^{-1/P} \quad (4)$$

where $P = 6$ is typically found to yield a good fit over the transition region [26–28]. This ensured that at the start of the century the correlating equation of Cranston et al. [4] applies, but over the 21st

Century the energy intensity and carbon ratio changed to reflect low carbon energy strategies implicit in the SRES scenarios. They therefore become progressively more influential as the century develops.

4.3. Interrogating the transition pathways

The projections of total environmental footprints (*per capita* footprint obtained from Eq. (4) multiplied by regional population size) on a regional basis are presented in Fig. 4. Currently the industrialised countries maintain a larger total footprint than the developing world, although the two regions converge at approximately the year 2015. However, beyond this point these regions diverge, with the 'majority South' accelerating towards much larger footprints than the 'North'. The developed world exhibits a much more gradual change in its environmental footprint. It reaches a maximum level of around nine billion gha in 2100 and a minimum level of just over one billion gha for the A2 and B1 scenarios storylines respectively. In contrast, the developing countries are responsible for approximately 75% of the worldwide environmental footprint by the end of the 21st Century, compared with only a 36% share at the turn of the Millennium. According to these scenarios the footprints for the industrialised and developing worlds seem unlikely to converge over this timescale. However, there is a tendency for the projections to converge sometime in the following century under the B1 scenario storyline (see Fig. 4). Here global population peaks by mid-21st Century, whilst the economy changes rapidly to a service and information economy resulting in lower material intensity. Global solutions are encouraged to ensure economic, social and environmental sustainability via the use of cleaner and more efficient technologies. The developing world continues to expand economically and socially, particularly under the A2 scenario. According to the IPCC, "economic growth is uneven" under their A2 scenario and it is this that gives rise to the irregular pattern in this projection. The A1 and B1 projections for the developing world show a turnaround in the total environmental footprint, and this is mirrored by the industrialised world for these storylines. It appears that the industrialised North (see Fig. 1) will undergo a change in their energy use and carbon emissions resulting in either a plateau in its total footprint, or indeed a reduction. The outlook for the developing world is less promising, as two scenarios show significant increases in total footprint with little evidence of a deceleration. However, if this region can be encouraged to be more environmentally conscious, there may be a chance to produce a shrinking footprint.

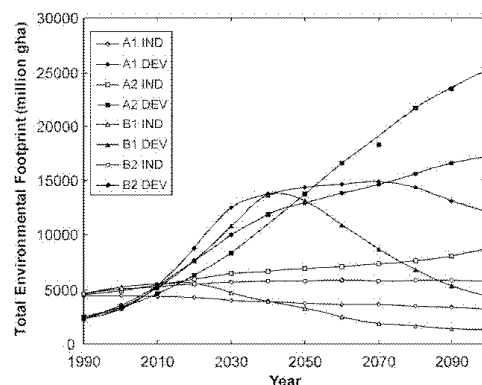


Fig. 4. Regional environmental footprints under the marker scenario.

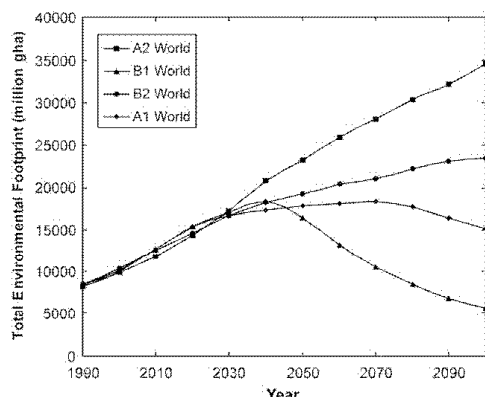


Fig. 5. Global environmental footprints under the marker scenario.

The situation in regard to the worldwide environmental footprint is illustrated in Fig. 5. This depicts the total global environmental footprint projected for a combination of both the developing and industrialised regions. The general trend is that the A1 and B1 scenario storylines suggest the possibility of a diminishing total environmental footprint from approximately 2040 onwards. The developing world has a larger population than the industrialised world, and therefore the environmental footprint *per capita* will be smaller. The scenarios with large population growth, such as the A2 scenario, have lower *per capita* environmental footprints. This masks the overall impacts of the total, far larger footprints that are associated with such high growth scenarios.

It has been shown that the present footprint projections indicate a reduction in the consumption of biophysical assets across both the developing and industrialised world. In order to achieve this in the 21st Century a serious commitment to GHG emissions reductions, and a greater dedication to environmental protection would be required in both the industrialised 'North' and the majority 'South' (as depicted in Fig. 1). This commitment must not only be in terms of a reduction of the *per capita* footprint, but also in terms of total environmental footprint as shown on a global scale for A1 and B1 in Fig. 5. That implies balancing population growth, economic well-being, and environmental impacts.

5. Concluding remarks

The 'natural capital' of planet Earth cannot replenish itself quickly enough to overcome the large deficit that is growing with every year and, on its current trajectory, will eventually no longer be able to cope with the demand. Environmental or 'ecological' footprints are indicators of resource consumption and waste absorption transformed on the basis of biologically productive land area required *per capita* with prevailing technology. They represent a partial measure of the extent to which the planet, its regions, or nations are moving along a sustainable development pathway. Such footprints vary between countries at different stages of economic development and varying geographic characteristics. A correlation equation for national environmental footprints has been used, alongside international projections of population growth and gross regional income, to estimate the relative contributions of the peoples of the North and South that would be needed in order to secure climate-stabilising carbon reductions out to about 2100. The four so-called 'marker scenar-

ios' produced by the Intergovernmental Panel on Climate Change were employed to estimate the degree of energy efficiency improvement and carbon mitigation that is feasible within the industrial and developing regions of the world (illustrated in Fig. 1). The present footprint projections suggest that a reduction in the consumption of biophysical assets across both the developing and industrialised world is indeed possible. The 'majority South' will dominate the world's environmental footprint well into the 21st Century as it develops and grows to meet the aspiration to improve the well-being of its peoples. The developing world's footprint overshoots that of the industrialised region by around 2010–2015. It then levels out and starts to fall, on the most optimistic scenario (B1), by about 2050. However, care must be employed when drawing insights from the projections presented here. They reflect smoothed trends across the current century and have the same weaknesses as associated with the SRES scenarios on which they are partly based (see Section 3 above). Large uncertainties are clearly involved in the modelling approach employed over such a long timescale. It is nevertheless envisaged that a low carbon future for the planet will fall within the broad range postulated in the present study, and that the four projections embrace the options that will be open to humanity (in both the North and the South) over the coming decades.

In order to achieve global sustainability a serious commitment to 'greenhouse gas' emissions (GHGs) reductions is required, and a greater dedication to environmental protection in both the industrialised North and the populous South. However, there is an intergenerational equity issue in relation to the contribution of the developed world. Carbon dioxide has a residence time of around 100 years in the atmosphere [1]. The build-up of atmospheric CO₂ concentrations is therefore largely a consequence of emissions released by the countries of the 'North' since the start of their so-called 'industrial revolution' around the turn of the 18th Century. The industrialised nations should therefore take the lead in mitigating the global release of GHGs, because they are principally responsible for their life-time concentrations. Environmental sustainability could and should, on equity grounds, be aided by the transfer of best practice energy technologies from the richer to poorer regions of the world [1]. These issues are at the heart of international negotiations aimed at providing a successor to the Kyoto Protocol, originally established under the United Nations auspices to stabilize GHG concentrations at a level that would prevent dangerous climate change. A new agreement will hopefully come into being post-2012 that will ensure a sustainable future for the people and wildlife on 'Spaceship Earth'.

Acknowledgements

The contribution of the first author (GRC) has been supported via the University of Bath's Strategic Investment Fund. The second author's research (GPH) on energy, environment, and sustainable development has recently been funded by research awards and contracts in the United Kingdom from the Carbon Trust, the Engineering and Physical Sciences Research Council (EPSRC), *e.on* UK (the electricity generator), the Great Western Research (GWR) Alliance, and the UK Energy Research Centre. He is presently the co-leader of a consortium of eight university partners (jointly with Prof. Peter Pearson, an energy economist from Imperial College London) funded via the *e.on*/EPSRC Strategic Partnership to study the role of electricity within the context of 'Transition Pathways to a Low Carbon Economy' [under Grant EP/F022832/1]. The work of this consortium has been particularly influential in focusing his attention on low carbon development into the 21st Century, albeit in principally in the UK context. Both authors are grateful to Gill Green for her assistance in preparing the figures.

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***Egalité, fraternité, soutenabilité*: evaluating the significance of regional affluence and population growth on carbon emissions**

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Abstract: Estimates of the relative contribution of population size and economic growth to global carbon emissions out to 2100 have been made for the industrialised 'North' and populous 'South' of the planet. This was achieved by decomposition of the terms in the 'sustainability' (or IPAT) equation. Historic data, alongside future IPCC emission scenarios, were used to analyse likely changes in CO₂ emissions over time. Economic wealth was found to be the most significant driver of such emissions in the industrialised world during the 21st Century. In the South, regional population and economic growth are each likely to play a significant role in affecting future levels of year-on-year carbon emissions. Nevertheless, the cumulative build-up of atmospheric CO₂ concentrations is largely a consequence of historic emissions released by the North since the start of its 'industrial revolution' around 1850.

Keywords: carbon emissions; economic growth; population size; future emission scenarios; international development; sustainability.

Reference to this paper should be made as follows: Cranston, G.R. and Hammond, G.P. (2010) '*Egalité, fraternité, soutenabilité*: evaluating the significance of regional affluence and population growth on carbon emissions', *Int. J. Global Warming*, Vol. 2, No. 3, pp.189–210.

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1 Introduction

It has been widely accepted amongst the scientific community that the growth in average global temperatures is mainly caused by the increasing anthropogenic Greenhouse Gas (GHG) concentrations (IPCC, 2007a), principally associated with the burning of fossil fuels. In 2005, CO₂ concentrations in the atmosphere were found to be 35% higher than 150 years earlier, with the bulk of this increase occurring since 1995. These rising CO₂ levels induce global warming, which degrades the environment and damages global ecosystems. The industrialised world has made the principal contribution to global CO₂ emissions to date, but this share is gradually decreasing as the rapidly emerging economies of the developing world grow at a faster rate. Indeed, for Asia alone, the carbon emissions more than doubled between 1990 and 2006 (IEA, 2008).

Collectively, the developing countries have a large population, with some 80% of the human population. This region of the world is consequently sometimes referred to as the 'Majority' South (see Figure 1). The bulk of the population in developing countries reside in rural areas. However, in the rapidly emerging nations, like China and India, the workforce is being urbanised as they adopt more advanced technologies for the development of their economies. If this transition towards industrialisation is undertaken in a 'sustainable' way (by, for example, making use of best practice, low carbon technologies secured (in part) from the developed or 'industrialised' world), it may be possible for the developing world to maintain a lower *per-capita* carbon footprint than the prosperous North (where only around 20% of humanity resides). It would appear that Southern 'fast learners' have a distinct advantage, since implementing something already invented is far easier than designing and developing new technologies from scratch. This may help to explain how the emerging economies, such as China and India, are able to gain so much ground on the leading economies in the North (Commission on Growth and Development, 2008). The growth rates for these developing economies of the South are higher than those already at the forefront of technological change, and they are rapidly approaching industrialised levels of material consumption (at least within their conurbations). These high-growth economies are able to converge with leading economies in terms of size as they have such large workforces. Many people in the rural part of the developing world are unemployed or underemployed, and therefore would welcome an opportunity for more 'productive' work in the cities. This represents a move not only towards industrialisation, but also to greater urbanisation (Commission on Growth and Development, 2008). During this high growth, industrialisation phase of development within the emerging countries of the South, there will be an inevitable increase in the *per-capita* CO₂ emissions. However, it may be possible to avoid carbon emissions rapidly increasing by encouraging the adoption of low carbon, mitigation measures to limit GHG emissions. Otherwise, it will be necessary to adapt to the adverse

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consequences of climate change – perhaps on a grand scale. Developing countries clearly desire to grow and provide a better ‘standard of living’ and well-being for their populations on equity or equality (*égalité*) grounds. They often find that suitable climate change mitigation measures are prohibitively expensive. China and India, along with other developing countries, are currently more dependent on ‘dirty’ fuels, like wood and coal – resulting in their relatively high carbon ratios (Cranston et al., 2010). Consequently, they need assistance from industrial countries to promote their economic growth (which will, in time, induce a ‘demographic transition’ (Nakicenovic et al., 2000)), as well as leading to an improvement in the resource efficiency of their energy systems. Environmental sustainability (*sustainability*) could, therefore, be aided by such a transfer of best practice energy technologies from the richer (Northern) to poorer (Southern) regions. This will ultimately be in the interests of all the citizens (*fraternité*) of ‘Spaceship Earth’ (Hammond, 2000).

It has been suggested that in developing countries, growth in economic wealth is assisted by a decreasing fertility rate, since economic development plays an important role in the demographic transition (Nakicenovic et al., 2000). Population growth is considered by some to be a key driver in increasing economic welfare, since it brings about a large workforce. However, this is not necessarily the case as other social and institutional factors, such as education and encouraging female work participation, have been shown to be significant in terms of long-term economic growth (Nakicenovic et al., 2000). Porritt (2007) has argued that the Peoples Republic of China (PRC) may have prevented the emission of many millions of tonnes of CO₂ into the atmosphere by implementing its ‘one child’ only policy. China will not reduce overall annual emissions under any international, post-Kyoto climate change agreement, although it is committed to establishing a ‘carbon intensity’ target (Cranston et al., 2010). They have also pledged to use 15% of renewable energy sources by 2020, and plant 40 million hectares of new forest as a carbon sequestration measure. But, their ‘one child’ population policy may also have a significant impact on reducing their carbon emissions going forward (Porritt, 2007).

Figure 1 The global north–south divide (The industrialised ‘North’ – black; the populous or majority ‘South’ – white with black edging)



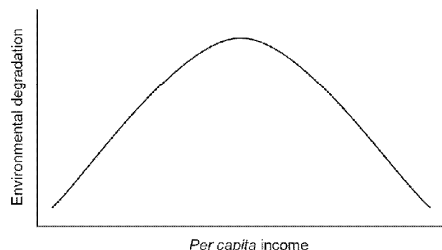
Source: Cranston and Hammond (2010)

The research community has mooted a variety of relationships between affluence (Gross Domestic Product (GDP) *per capita*) and environmental quality. Thus, the importance

of economic development in improving or degrading the environment has been ‘hotly’ debated. One argument is encapsulated in the ‘Kuznets Curve’ hypothesis (Figure 2), whereby the relationship between environmental protection and economic welfare is purported to follow an inverted-U, or bell-shaped, curve (Huang et al., 2008). This curve shape is said to represent the situation in those developing countries that have an increasing national income, alongside increasing environmental pressures. As they industrialise, there appears to be a stronger demand for ‘greener’ goods and environmental regulation with the take-up of low impact (or carbon) technologies stimulated by the availability of more economic resources for investment. This tends to break down the link between economic growth and environmental degradation, and hence the downward turn of the Kuznets Curve at higher *per-capita* income (Figure 2). It would be reflected, for example, by the commitment of the Government of the PRC (Cranston et al., 2010) to establishing a ‘carbon intensity’ target for the immediate post-Kyoto era.

The aim of this work was to determine whether it is population growth or economic wealth that contributes most significantly to carbon emissions in various regions of the world. This would indicate, in particular, the relative magnitude of the climate change impacts that are more likely to be caused by the wealthy ‘North’ and the developing ‘South’ over the coming century. These drivers for carbon emissions were assessed using the so-called ‘sustainability’ or IPAT equation (Ehrlich and Holdren, 1971), together with an evaluation of past and future trends. Historic data was employed to reflect past performance, while four different ‘marker’ scenarios produced by the United Nations’ *Intergovernmental Panel on Climate Change* (IPCC) in its SRES (Nakicenovic et al., 2000) were used to study likely trends out to the year 2100.

Figure 2 Kuznets Curve hypothesis



2 The sustainability or ‘IPAT’ equation

The generic links between environmental burdens or impacts (I) flowing from a population of a given size (P), its economic wealth or affluence (A), and the extent and efficiency with which it uses resources and technology (T) were encapsulated in a simple equation devised by Ehrlich and Holdren (1971): $I = PAT$. It has more recently been termed the ‘sustainability equation’ (Hammond, 2000). Affluence (or economic consumption by an average individual) has traditionally been measured by economists using the concept of the GDP on a *per-capita* basis. In the period since the early 1960s, this has tended to increase over time in the wealthy countries of the industrialised world (the North; see Figure 1), whilst typically falling in many of the poorer nations in the developing countries of the South. The population size has remained almost stable in the

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affluent countries of Northern Europe. In contrast, rapid population growth has been observed in many parts of the developing world: Africa, continental Asia, and Central and South America. The 'technology' component in the IPAT equation represents the environmental damage per unit of consumption (or GDP). To determine CO₂, or other pollutant emissions, an extension to the IPAT equation, known as the 'Kaya identity' (Kaya, 1990), is often employed:

$$\begin{aligned} \text{CO}_2 &= \text{Population} \times \frac{\text{Economic Wealth}}{\text{Population}} \times \frac{\text{Energy Use}}{\text{Economic Wealth}} \times \frac{\text{CO}_2}{\text{Energy Use}} \\ C &= P \times G \times \text{EI} \times \text{CR} \\ C &= P \times G \times F \\ \text{where } F &= \frac{\text{CO}_2}{\text{GDP}} = \frac{\text{CO}_2}{\text{Energy Use}} \times \frac{\text{Energy Use}}{\text{GDP}} \\ &= \text{EI} \times \text{CR}. \end{aligned} \quad (1)$$

In the above-mentioned equation set, C is carbon emissions (GtC), P is population (million), G is *per-capita* GDP (\$, 1990 'International (Geary-Khamis) Dollars' Market Exchange Rate (MEX)), EI is energy intensity (MJ/\$) and CR is carbon ratio ($\mu\text{g C/J}$); see also Hammond (2006) or Cranston et al. (2010). Waggoner and Ausubel (2002) refer to equation (1) by the acronym 'ImPACT'.

It has been noted by York et al. (2003) that the determinants of carbon emissions are inextricably linked, such that each variable does not influence the emissions independently. Thus, to understand the relative significance of each parameter, their potential rate of change has to be assessed. This multiplicative form of the Kaya identity can be manipulated, such that growth rates in each parameter are additive (Gurer and Ban, 1997; Nakicenovic et al., 2000). For example, CO₂ emissions from mid-19th century have grown by approximately 1.7% per year (Nakicenovic et al., 2000; Nakicenovic, 2000). This can be broken down into the individual factors, such as:

$$\begin{aligned} 1.7\% &= 1\% \text{ population increase} \\ &+ 2\% \text{ growth in } \textit{per capita} \text{ income} \\ &+ 1\% \text{ decline in the energy intensity} \\ &+ 0.3\% \text{ decline in the carbon ratio.} \end{aligned}$$

This has been described mathematically by Gurer and Ban (1997) taking the assumption of continuous changes in each parameter of the Kaya identity, and then rearranging the equation (by taking natural logarithms) and applying subsequent differentiation to yield equation (2).

$$\frac{dC}{C} = \frac{dP}{P} + \frac{dG}{G} + \frac{d\text{EI}}{\text{EI}} + \frac{d\text{CR}}{\text{CR}}. \quad (2)$$

The mathematical manipulation used here is presented in full in Appendix. In a similar manner, Raupach et al. (2007) defined the proportional growth rate of a quantity $X(t)$ as $r(X) = X^{-1}dX/dt$ (with units $(\text{time})^{-1}$), the counterpart of the Kaya identity for proportional growth rates is shown in equation (3).

$$r(C) = r(P) + r(G) + r(\text{EI}) + r(\text{CR}). \quad (3)$$

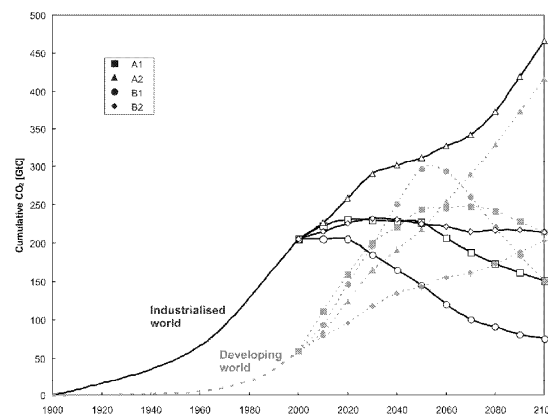
The global emissions (C) can, therefore, be expressed by the summation of the above-mentioned factors. Through this analysis, it is possible to determine which parameters contribute most to the growth in CO_2 emissions.

The growth rates utilised here were evaluated from a base year of 1990, and then added cumulatively to the end of the century. This was achieved via the above-mentioned decomposition of the terms in the IPAT expression (equation (1)). Each driver was assessed to establish, which gave the most significant contribution to the growth of carbon emissions over the 21st century. Both historical data and the IPCC scenarios (Nakicenovic et al., 2000) for the developing and industrialised world have been employed in the current study.

3 Cumulative atmospheric carbon

To understand the effects of population growth and economic prosperity upon the emissions of CO_2 into the atmosphere, a long timescale needs to be adopted. Since the start of the 20th century, CO_2 emissions from the developed world (the North; see Figure 1) have been significant, whilst this region underwent its industrial revolution. CO_2 remains in the atmosphere for, or has a 'residence time' of, up to 100 years (Hammond, 2000), and therefore accumulates over time. Thus, although the developing regions are rushing to industrialisation, the world is still suffering from the effects of the prosperous North's own industrial expansion. Indeed, Figure 3 illustrates that in terms of cumulative carbon, the majority South would not reach equivalent levels to the North until approximately the middle of the 21st century. This is in spite of the fact that their total emissions each year are likely to rise well above that of the North well before this time period (see also Cranston and Hammond (2010)). It demonstrates the need for the industrialised North to lead the way in transferring clean (or 'leapfrog') technologies to the developed world (Hammond, 2000).

Figure 3 Cumulative carbon emissions for industrialised and developing world



A variety of information sources have been employed to provide historical data for the present analysis. Trends in anthropogenic carbon emissions were established

from regional data for the developing and industrialised world from CDIAC databases (Marland et al., 2008). Fossil-fuel emissions were adopted to reflect the impacts of gas, liquid and solid fuels, as well as emissions from gas flaring and cement production where appropriate. These emission estimates were expressed in Giga Tonnes of Carbon (GtC). Population data for the early 20th century was taken from two sources: National Academy of Sciences, 1971 and United Nations Department of Social Affairs Population Division, 1953. These data sets only go up to 1950. Data post-1950 was obtained from the UN (Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat, 2009). Economic wealth was measured in terms of 1990 International (Geary-Khamis) Dollars, a monetary indicator that is similar to Purchasing Power Parity (PPP) adopted, for example, by Hammond (2006). Trends in *per-capita* economic wealth were taken from a comprehensive database (Maddison, 2009). The use of this detailed database was justified in his most recent book (Maddison, 2006). There were no readily available Energy Intensity data from 1900. However, it was possible to find the corresponding Carbon Intensity ($I = \text{CO}_2/\text{GDP}$) values via the combination of energy intensity and carbon ratio by using the Kaya identity (equation (1)) since each factor can be summed to yield the change in carbon emissions.

Much of the data collected were taken from regional statistics, and had to be adjusted and summed to give the totals for the majority South (developing world) and the prosperous North (industrialised world), respectively; see also Figure 1. The breakdown between regions was as follows:

<i>Developing South</i>	<i>Industrialised North</i>
Africa	Australia, Japan and New Zealand
Asia Pacific (less Australia, Japan and New Zealand)	Eastern Europe (former Soviet Union and its satellites)
Central & South America, and the Caribbean Nations	North America
Middle East	Western Europe

This represents a similar North–South aggregation to that used by Cranston and Hammond (2010) for their regional projections of ecological or environmental footprints.

4 Scenarios: indicators of future pathways

4.1 Scenario analysis

Scenarios can be developed to evaluate future changes in systems that are unpredictable, lack understanding, or have large scientific uncertainties. It is for these reasons that emissions scenarios have been formulated. There is a degree of uncertainty surrounding the physico-chemical processes involved with climate change, in particular the way in which anthropogenic emissions affect the atmosphere and respond under different energy futures (Cranston and Hammond, 2010). The IPCC (Nakicenovic et al., 2000) developed a varied selection of future GHG emission scenarios. These are not predictions or forecasts, but are a suggestion of alternative futures. They are formulated using a set of reproducible assumptions based on historical trends, physico-chemical relationships and driving forces. Such scenarios range in complexity from baseline ‘storylines’, and

consider a variety of plausible options. Thus, a selection of future emission paths from low to high can be assessed with respect to future response policies (Nakicenovic, 2000).

There is a vast array of scenarios that can be found in the literature: covering narrative descriptions, quantitative scenarios and detailed models (Cranston and Hammond, 2010). Scenarios are frequently used in the private sector, and the focus of the IPCC studies has obviously been on GHG emissions, principally CO₂. This enables the study of future energy-related industrial developments, and the way in which the resulting GHG emissions may impact on climate change over a given period.

4.2 The four marker scenarios

The IPCC developed a large variety of scenarios for assessing the different pathways that GHG emissions may follow up to the year 2100. The scenarios are all documented within the IPCC's SRES (Nakicenovic et al., 2000). However, they produced four main themes or 'storylines' that enabled different scenarios to be grouped together. These storylines follow different economic, social, environmental, demographic and technological interpretations of likely futures. In total, there were 40 separate scenarios that the SRES devised from a given baseline. None of these are highlighted as being the 'best' or 'worst' cases, or the most likely. They were all considered by IPCC Working Group III as being equally plausible, and illustrative of different storylines. Despite this, a 'marker' scenario from each group was selected, based on those scenarios that best reflected the given storylines. The marker scenarios have undergone the highest level of assessment and scrutiny by the SRES writing teams in an open process. Marker scenarios were carefully selected on the following basis (Nakicenovic et al., 2000):

- the SRES marker scenarios were chosen to represent the full range of emission paths
- a choice of initial quantifications (by the modellers) was selected that best reflected each SRES marker storyline
- the preferences of some of the SRES modelling teams, and features of specific models, were used to define the four different markers.

Many researchers focus on the four markers in their work (see, for example, van Vuuren and O'Neill (2006)), and therefore were selected for present analysis, as well as for the earlier one of regional environmental footprints by Cranston and Hammond (2010).

The four SRES marker storylines are each characterised by different patterns in terms of population growth, economic welfare and global emissions (Nakicenovic et al., 2000): each following a different pathway into the future. The scenario and storylines vary significantly; they range from high to low global populations, rapid economic growth and technological development, to benign environmental strategies or otherwise. The four storylines are labelled as A1, B1, A2 and B2. The A1 storyline represents a world with rapid economic development and growth, together with the implementation of advanced, energy-efficient technologies. Population was projected to peak in the mid-21st Century, and then begin to decline. An international perspective was taken as the people of both regions were assumed to begin to experience greater social interaction and a reduction in economic disparities. The A2 scenario family assumes much more self-reliance amongst the regions, with less economic, social and cultural interaction than was associated with A1. Population rises continuously to high levels. The B1 storyline follows the same 'peaking' population pattern as A1, as well as the convergence in the size of the

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economies between regions. However, a high level of environmental and social consciousness is assumed, with a global consensus on the need to secure sustainable development (see also Cranston and Hammond (2010)). There is an emphasis on implementing a service and information economy with clean and efficient technologies to be sparing in the consumption of natural resources. In a similar manner to B1, the B2 storyline focused upon economic, social and environmental sustainability, but this time at a more regional level, focusing on local solutions. Population is assumed to grow continuously, but at a slower rate than the A2 situation, and economic development is taken to be at an intermediate level.

4.3 North–South: the developed and developing regions of the world

In this work, the scenarios were separated into the developing and industrialised (or ‘developed’) regions of the world, so that the wealthy ‘North’ could be compared with the poorer, but more populous, ‘South’ (see Figure 1 and Section 3). The growth in population size and economic wealth within the two regions has differed quite significantly over time. Future population growth in the industrialised world was very similar for all four of the SRES marker scenarios, with the total population size remaining almost constant during the 21st Century. This contrasts sharply with the developing countries where, in both the A1 and the B1 scenarios, the population peaks and then begins to fall around 2050. The A2 and B2 scenarios assume a continuous population growth, with the A2 scenario incorporating a very sharp rise (‘boom’) in the number of people in the developing world. The marker scenarios display continuity with the historic data collected for carbon emissions and population growth.

Economically, the developing world has been growing faster than the industrialised countries over recent decades. But, each of the marker scenarios reflects different rates. Thus, A1 implies a huge rise in economic wealth for the South, whereas A2 is far more modest. The industrialised North follows a more moderate growth pattern under each scenario, but with the A1 scenario displaying a significantly higher affluence than the other scenarios at the end of the 21st century. A potential difficulty arose in ensuring continuity of economic growth projections with historic data. The latter was measured in PPP equivalent terms, whilst the IPCC utilise MEX. However, this was not an issue when looking at percentage change, or growth, as these are dimensionless. Both indicators were found to be appropriate, and could be used interchangeably when applied in this manner. An ongoing debate in the literature has surrounded the way in which the income projections adopted by the IPCC were expressed in terms of MEX, rather than PPP. The SRES working group (IPCC, 2003) considered that over long time periods the rates of economic growth in terms of MEX and PPP tend to converge for less-developed regions. Studies have shown that the choice of exchange rate for GDP does not greatly affect the projected GHG emissions if used consistently (IPCC, 2007a, 2007b). Indeed, despite being one of the most hotly debated aspects surrounding the SRES scenarios, the economic growth trends do not vary significantly (IPCC, 2007a).

4.4 The driving forces behind the scenario variants

It may appear from the IPAT equation that carbon emissions grow linearly with population, but the interactions between each component are actually more complex, particularly in terms of demographics and economic growth. Many of the factors

are interlinked; for instance, demographic changes are related to differing social and economic developments. Fertility and mortality trends are dependent on income, education and health education, and these in turn affect the size and age of populations (Nakicenovic et al., 2000). Advances in technology cause improvements in economies in terms of productivity and growth. These all suggest that affluence and technology are coupled identities, and cannot be strictly treated as totally separate within the IPAT equation or Kaya identity. Income was also assumed to be closely linked to pollution abatement by the IPCC (Nakicenovic et al., 2000). A rise in income was considered to induce an initial rise in pollution but, with greater concern about environmental protection over time, this would gradually lead to a reduction in emissions in line with the precepts of the Kuznets Curve (see Figure 2). Technology, social and economic changes are often regarded as enabling growing populations to live within their restricted resources or 'limits'. Such innovations occurred, for example, during the Industrial Revolution, when the use of coal enabled through changes in 'heat engine' technology. This had adverse impacts on the environment in Britain during the 1800s (Hammond, 2000), but human priorities are more likely to be different in the latter part of the 21st century with a greater focus on the need for climate change mitigation.

4.4.1 Population projections

The key drivers behind changes in population size include aging, urbanisation, the provision of health services and the spread of diseases (like AIDS). These lead to changes in fertility and mortality rates. Fertility is regarded as being the most important factor affecting population size. Many scenarios assume a decrease in world averaged total fertility rate (the average number of births per woman). A small change in fertility rates can cause a massive variation in future populations. Fertility rates are expected to continue to decrease in developed regions, such as Europe. However, demographers believe that this may be due to women deciding to delay childbearing until their later years, and as such the total fertility rate may begin to stabilise or rise again in the long term. Population is also linked to other factors, such as economic welfare and emissions. Indeed, Gaffin and O'Neill (1998) argue that CO₂ emissions are strongly affected by population growth. In terms of economic growth, the common assumption is that wealthier countries have a relatively low fertility rate, whilst those poorer countries tend to have higher fertility rates on average. As countries develop economically, they undergo a 'demographic transition' (see Section 1). Goods and services become more readily available, and material consumption tends to increase. There is then a shift from high to low fertility as families make the choice to consume more, as opposed to having more children; this process is often coupled with urbanisation.

4.4.2 Economic development

Countries throughout the world are at varying stages of economic development (Hammond, 2006). Some have entered the stage of mass-consumerism, such as the USA. The rapidly emerging economies, including China, are undergoing transition (Nakicenovic et al., 2000): catching up to the 'productivity frontiers' of the developed world. The less-developed countries in the South, like Mozambique, have very low productivity levels, particularly in their agriculture sectors, resulting in slow economic growth. Increases in population size are sometimes regarded as a driver of development,

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because it offers a larger workforce. But, there are actually a number of other social and institutional factors that bear on this. They include, for example, encouraging female participation in the workforce and education provide opportunities for economic stimulation and encouraging social improvement in the long term. In contrast, an aging populace results in a smaller workforce to develop the economy. However, this often represents only percentage change and not total numbers. Thus, there may still remain an adequate labour force, especially as female participation rates increase. The most important characteristic of the workforce may not therefore be the number of participants, but qualitative factors like education. These characteristics ensure continuous development and growth of economies in the long term via improved productivity.

Advances in technology often require a social acceptance that enables discoveries and innovations to move forward and be implemented. Barro and Sala-i-Martin (2004) have highlighted the relationship between economic growth and law enforcement; they argue that legal rights and democracy are necessary for markets to be successful and enhance growth. Of course, it is difficult to quantify such social issues in terms of monetary value, but these factors need to be taken into account in different scenarios. Through the use of the 'storylines', the SRES was able to set frameworks that describe social and cultural variations explicitly (Nakicenovic et al., 2000). Improvements in technology drive forward growth in productivity and increase economic output (Barro and Sala-i-Martin, 2004). Indeed, GDP grew by 63% between 1947 and 1973 in the industrialised countries of the *Organisation for Economic Co-operation and Development* (OECD), as a result of technological change and advancement (Barro and Sala-i-Martin, 2004). This growth rate slowed down beyond the 1970s as the OECD moved beyond industrialisation to a service-orientated economy. It was suggested by Nakicenovic et al. (2000), on the basis of empirical evidence, that energy and material intensities are closely related to macroeconomic productivity. This implies that high GDP *per capita* is associated with lower energy and materials intensities. The SRES utilised this relationship where overall economic productivity growth and reductions in energy use per GDP are well linked.

4.4.3 *Energy end-use and land use*

Energy use and emissions are frequently represented in terms of major end-use sectors (see, for example, the representation of the UK energy sector by Hammond (2000)). There are significant differences between sectors and also between regions of the world. Industry is a key sector, as well as residential communities, commercial services and transportation. There are a variety of drivers for energy use, which include economic drivers, energy intensities, population size and urbanisation. These factors are individually driven by consumer choice, energy costs, technical progress, infrastructure, and of course economic conditions.

Energy intensity can be improved by the adoption of advanced energy-saving techniques (Hammond, 2000). This is the case in many industries, such as construction, manufacturing and transportation. Lovins (1996) suggests that major improvements in energy and resource use efficiency can be achieved, which he argues are often cheaper to make than to make more modest ones. These major improvements can often be realised in a relatively short time-span: perhaps between 10 and 15 years. Carbon emissions resulting from energy use are dependent on the carbon intensity (or emissions coefficient) of the energy resource utilised (Nakicenovic et al., 2000). The carbon intensity changes as fuels substituted (e.g., high to low carbon fuels

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(coal → natural gas)), as well as with advances in end-use technologies and processes. There was a move towards less carbon-intensive fuel among the highly industrialised countries between 1971 and 1992 (Ang and Pandiyan, 1997; Schipper et al., 1997). Emissions increased during that time period, but at a slower rate than the growth in the economies of the OECD nations (Schipper et al., 1997). The resultant fall in energy intensities implied a move from coal and oil, as well as a marked reduction in energy-intensive manufacturing. This is not the case for some of the rapidly emerging economies, for example the PRC, where there is still high dependency on coal for its energy supply. However, some developing countries have been able to make the move away from dirty fuels to alternative fuel types. South American nations, for example, make a significant use of hydropower.

Buildings typically use a large proportion of end-use energy (Hammond, 2000). The end-use requirements are driven by factors such as population, dwelling size, number of residents and commercial floor space. As nations move towards urbanisation, there is an increase in the energy requirements for lighting, heating/cooling and refrigeration. Energy consumption is strongly correlated to income levels (Nakicenovic et al., 2000), and therefore the building sector in industrialised countries tend to have higher levels of consumption, owing to the increased number of relatively large homes, heating systems and appliances. Space heating is an important end-use for many of the industrialised countries (Hammond, 2000), although this is a less common requirement in developing countries. An exception is the PRC, where heating accounts for half of the residential and commercial building energy demand. In the developing world generally, the basic need for cooking and water heating dominate the energy use in buildings.

Transportation clearly has a high energy (oil) demand, and is continuously growing (Hammond, 2000). Factors that affect transportation emissions include travel activity, energy efficiency, and other technological advances that lead to carbon intensity improvements: advanced powertrains, lightweight bodies, and the like. Transport energy demand is directly related to economic activity, settlement patterns and price of fuel. Future developments in telecommunications in the developed world may change the way that societies organise their travel infrastructures. People may then no longer have to travel to work, but can facilitate home-working. The internet also plays an important role in reducing travel needs, for example online shopping permits people to make purchases without needing to travel to stores.

Land use change contributes to GHG emissions. Activities include deforestation, afforestation and changes in agricultural management. Deforestation is one of the main factors that affect the sequestration of anthropogenic CO₂ emissions. These can arise from the burning of forests and clearing of vegetation, for example, in the agricultural sector. The developing regions of the world tend to have a more significant problem with deforestation than the industrialised nations; a classic example being the devastation of the Amazon rainforest.

5 Determination of the most significant driver of carbon emissions

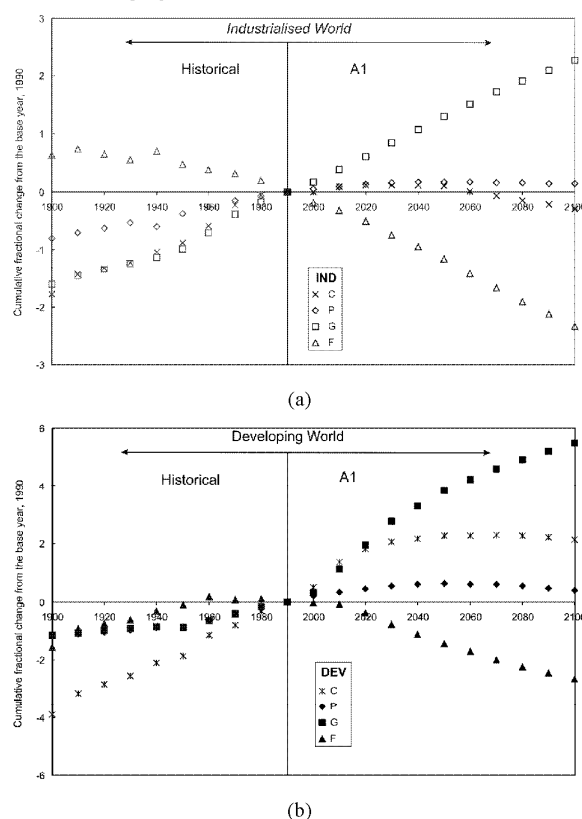
5.1 The approach

The rise in CO₂ emissions can be attributed to increasing worldwide economic prosperity and the expanding global population. The significance of these two factors is argued

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to vary between the developing and industrialised world. The IPAT formula of Ehrlich and Holdren (1971) and the related Kaya identity – equation (1) – were utilised to evaluate which of these parameters is the principal determinant or driver of CO₂ emissions. The rate of change in the trajectory of each determinant was evaluated, using both historical data and future scenarios: the Marker Scenarios developed for the SRES. These data sets were manipulated to determine the various parameters in the Kaya identity (equation (1)): energy intensity (EI) (MJ/\$), carbon ratio (CR) (μgC/J) and GDP/capita (G) and subsequently carbon intensity (F) (gC/\$). The base year of 1990 was chosen, and all data was normalised around this date, i.e., the growth, or change, in each factor has been examined relative to this base year. The gradient of each line represents the relative growth or decline of that determinant. For example, the trends for economic wealth historically and in the A1 scenario show a growth in economic prosperity for both the industrialised and the developing world (Figure 4). A similar approach was recently adopted by Raupach et al. (2007), who studied the drivers of carbon emissions both globally and in a number of sub-regional groups.

Figure 4 North–South cumulative change in carbon emissions relative to the base year of 1990 – historic data and A1 scenarios for (a) the industrialised and (b) the developing world



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5.2 *Past contributions to carbon emissions*

Population and economic growth have both historically contributed to the increase in carbon emissions in the industrialised and developing world. Over the 20th Century, economic wealth has been the major contributor for both regions. Growth in economic prosperity in the wealthy North dominated the emissions of carbon throughout the century; population played only a smaller role indicated by the less steep gradient and smaller magnitude (as shown in Figure 4). Here, the y-axis represents the cumulative value of the fractional change of each factor from the base year of 1990. The change of each factor between decades, for example population, was then determined via:

$$\text{Cumulative \% population growth} = \left(\frac{P_x - P_{n+10}}{P_{n+10}} \right) + \left(\frac{P_{n+10} - P_n}{P_n} \right)$$

where n = base year, 1990
 x = decade under analysis. (4)

The trends in the industrialised North contrast with those in the majority South, where population and economic growth were both found to be significant drivers of carbon emissions in the 1900s (see again Figure 4).

Population had a marginally more significant effect on carbon emissions during the first half of the 20th century for the South. However, the rise in population and affluence became more balanced by the turn of the millennium. Beyond this point, wealth became the most important determinant of carbon emissions. Given that the carbon intensity has not improved (fallen) very much in the developing world, carbon emissions tend to follow the combined influence of economic and population patterns. In the industrialised world, carbon emissions were limited by the impact of improved energy efficiencies and the knock-on fall in the carbon intensity. These past trends are in agreement with those of Gurer and Ban (1997), who showed that economic prosperity is the greatest contributor to the rise in CO₂ emissions for the OECD countries in the second half of the 20th Century.

5.3 *Future differences between the 'North' and 'South'*

5.3.1 *Scenario analysis and interpretation*

There have been a number of attempts to predict for the future growth of the developing and industrialised countries, and the way in which this may affect their carbon emissions. The four SRES 'marker' scenarios selected for this study were evaluated to assess the different influences of population and economic welfare for the developing and developed worlds to the end of the 21st century. Economic development was found to be the largest contributor to growing carbon emissions in the industrialised world under all four 'marker scenarios' (see, for example, Figures 4(a)–6(a)). The economic growth rates are high, with magnitudes far larger than those for population. Indeed, Figure 4(a) illustrates that population growth has a much smaller influence on the carbon emissions in the prosperous North. This was expected, as the industrialised countries of the North continue to grow economically, whereas their population sizes remain relatively constant. Despite this increase in affluence, developed world carbon emissions were not seen to grow rapidly (e.g., exponentially). Instead, the carbon intensity effectively limits the total

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carbon emissions as efficiency improvements are more likely to be implemented in the future. For the industrialised world, three of the scenarios indicate that carbon emissions will peak, and then fall again by the end of the 21st century (see, for example, Figure 6(a)). The only exception is in regard to scenario A2, which implies greater self-reliance amongst the regions (Figure 4(a)). Thus, carbon emissions are being driven up by economic growth, but this is counteracted by improving (reducing) carbon intensity levels. The industrialised world is technologically advanced, and has the requisite financial resources to invest in energy and carbon reduction strategies. For instance, increased use of nuclear power and renewables facilitates a low carbon energy mix, and therefore fewer pollutant emissions. The SRES A2 scenario is the only storyline that displayed continuously increasing carbon emissions in the industrialised world. This may be due to the underlying assumption that energy intensity reduces later in the 21st century at a faster rate than for other scenarios (Figure 5(a)).

Figure 5 North-South cumulative change in carbon emissions from the base year of 1990 – A2 Scenarios for (a) the industrialised and (b) the developing world

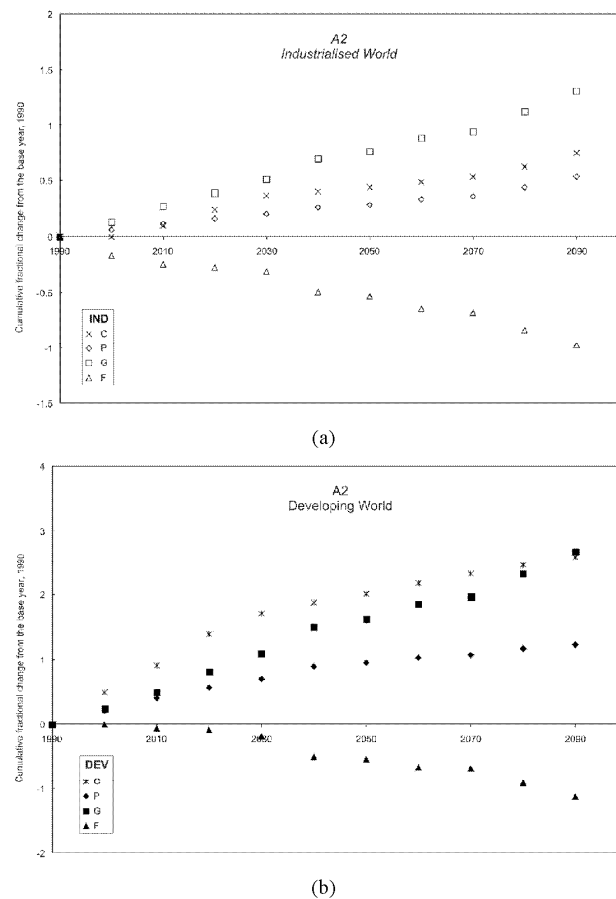
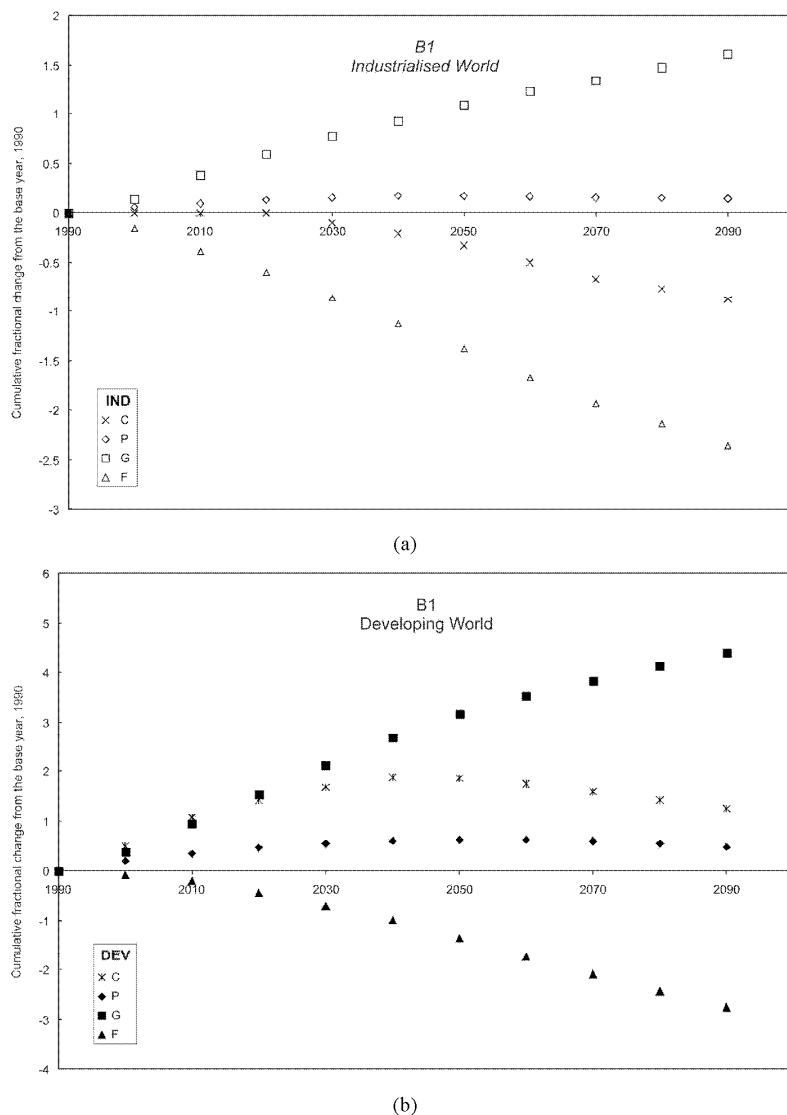


Figure 6 North–South cumulative change in carbon emissions from the base year of 1990 – B1 scenarios for (a) the industrialised and (b) the developing world

In the populous South, the likely influence of economic and population growth on future carbon emissions is clear in the 21st century. Economic growth was found to be the main driver of carbon emissions (see Figures 4(b)–6(b)). Population no longer plays such a dominant role in this regard. The population size of the Majority South is predicted to peak, and then decrease, for the A1 and B1 scenarios. In contrast,

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population growth is shown to slow down under both the A2 and B2 storylines. The results here are in agreement with those of Shi (2003): the impact upon emissions from population growth was far more pronounced in developing countries than in developed countries. Shi (2003) found that the growth in CO₂ emissions outpaces population growth in both the industrialised and the rapidly emerging economies over the period 1975–1996; this was more pronounced in the case of the latter countries. Rather like the industrialised North, the carbon emissions from the developing South are assumed to be restrained from reaching very high levels by improvements in carbon intensity in the future. The B1 scenario (Figure 6(a)), a pathway to a more environmentally conscious world, shows the greatest reduction in carbon from the industrialised world. A focus is assumed to be on environmental strategies, with investments being made in green technologies. The developing world also exhibits a large negative gradient in carbon intensity, which is then reflected in the eventual reduction of emissions by around 2100. As the developing world industrialises with growing wealth, they need (on climate change mitigation grounds) to become more resource-efficient, and utilise technological advancements to ensure improvements in energy intensity that result will significantly reduce carbon emissions.

The growing population and economic size of the developing world will cause its year-on-year CO₂ emissions to rise at a faster rate than in the industrialised world. The cumulative or historic carbon emissions that result are likely to peak, and then begin to decrease for both the industrialised and the developing worlds under the A1 and B1 scenarios (compare and contrast Figures 4 and 6). This is due to the presumed global commitment to sustainability, greater internationalisation, and a convergence of regions implied by the SRES marker scenarios. The A2 and B2 storylines maintain an upward trend in carbon emissions for the developing countries (see for example Figure 5(b)). This is caused by the large growth in population, particularly in the case of the A2 storyline, with little interaction between regions. Both of these scenarios assume a degree of self-reliance, together with local solutions to energy and environmental problems. The rate of knowledge transfer and technological advancement is, therefore, slower than might otherwise be the case, with consequent low uptake in resource efficiency and carbon reduction measures.

5.3.2 *Some controversial issues*

Pearce (2010) has recently discussed the possibility of population ‘crashes’ or ‘famines’ in his book ‘Peoplequake’. Taking Europe as an example, the population appears to be reaching its peak. For centuries, this region has seen a continuous growth, and a serious downturn would therefore be of concern for a number of reasons. Already, many countries rely upon foreign immigration to maintain their economies, without having to increase indigenous fertility rates to above the replacement levels. A downward spiral in fertility is dangerous as there become fewer women to procreate and maintain population levels. Potential falls in population size might arise from further urbanisation, ultimately leading to another type of ‘demographic transition’ in affluent countries. This could have some positive benefits. Brand (2005), for example, suggests that city living should be encouraged, as it allows rural areas to be replenished. He argues that efforts should be made to permanently protect rural environments. This could be more easily achieved with a smaller overall population in Northern countries. It has been estimated that future world populations could potentially be reduced by something like 400 million

people by 2100 if proper family planning was made available to all those that need it (Bongaarts et al., 1990). This was based on findings that over the past 20 years family planning in the developing world was able to reduce the current population by approximately 40 million people.

This study has confirmed that industrial development and consumption in the North is the main cause of cumulative or historic CO₂ emissions. Kuznet's hypothesis (see Figure 2) may well kick-in in the South as the developing world heads towards greater economic prosperity by the end of the 21st century. Improvement in environmental quality, due to diminishing carbon emissions, can be seen for the majority of scenarios. The reductions in emissions are most pronounced under the B1 scenario (see Figure 6(b)), because of heightened environmental awareness presumed in this SRES storyline. The developing world should, therefore, be able to invest in clean, efficient technologies and encourage environmental regulation as it industrialises and grows economically. This results in a reduction of historic carbon concentrations in the atmosphere for all the marker scenarios (see Figures 4–6). Economic growth and development are vital prerequisites for improving basic living standards. This is undoubtedly the case for those countries in extreme poverty with near-starvation conditions. However, for the developed world, a growth in wealth may not necessarily be advantageous for planetary sustainability. This is highlighted by the A2 marker scenario for the industrialised world (Figure 5(a)). Cumulative carbon emissions are seen to grow continuously despite improvements with efficiencies and technologies that give rise to a fall in the decreasing carbon intensity. The SRES A2 marker scenario postulates economic growth with little investment in environmental protectionism. It offers an excellent example of a future world that is highly affluent, but with little consideration for the environmental consequences of humanity's lifestyle choices, resource use, or carbon emissions.

Simms et al. (2010) argue, using a 'pet hamster' as an analogy, that indefinite global economic growth is unsustainable. A hamster doubles its weight from birth to puberty each week (approximately six weeks after birth). If the hamster continued to double its weight every week, it would reach a mammoth mass of 9 billion tonnes on its first birthday. In nature, this is not possible, as once animals reach maturity their weight levels off. An analogous limitation could apply to the global economy, since continuous growth is pushing the planet beyond its natural capital and its safe limits. A change in development is illustrated by the results for B1 scenario (see Figure 6). Here, strong environmental protectionism, as well as a good level of social consciousness, leads to a reduction of income inequalities. In this scenario, carbon emissions are reduced by the end of the 21st century for both developed and developing nation States. As the developing world completes its industrialisation, emissions continue to grow along with wealth, but by the mid-century investments are assumed to be made in climate change mitigation measures that move humanity in the direction of a more sustainable world.

6 Concluding remarks

It has been shown, using a decomposition of the terms in the IPAT equation (of Ehrlich and Holdren (1971)), that population and economic wealth both contribute to the growth in carbon emissions associated with developing and industrialised countries. For the industrialised world – the prosperous North – it was found that affluence

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(measured in GDP *per capita*) was the most significant driver of CO₂ emissions from both historic trends and future projections/scenarios. In the case of the developing countries – the Majority South – the distinction between population and economic growth was less clear. Historically population and economic growth were seen to be the main drivers, but as the world begins to converge economically during the 21st century affluence, reflected in *per-capita* industrial capacity and material consumption, may start to play a more significant role in driving up carbon emissions from the developing world. Despite the differences observed between the four marker scenarios, the findings regarding the influence of population and GDP *per capita* were similar for each storyline. It appeared that economic growth is the dominant driver of the carbon emissions in the industrialised regions. As the developing world heads towards industrialisation at the end of the 21st century, economic prosperity is more likely to have a far greater impact on annual carbon emissions than population growth. The growth in population size and economic wealth in the developing world will eventually cause year-on-year carbon emissions to rise at a faster rate than the industrialised world. Similar observations were recently made by Raupach et al. (2007) in their study of the drivers of carbon emissions, both globally and in a number of sub-regional groups. The improvements in energy efficiency and resource productivity counteract the effects of the rise in affluence and population size on the growth of atmospheric carbon concentrations. As technological advances are implemented, the energy intensity will fall, resulting in a reduction in the carbon emissions for each region.

To achieve global sustainability, a serious commitment to GHG emissions reduction is required, and a greater dedication to environmental protection in both the industrialised North and the populous South. However, there is an issue of intergenerational equity in relation to the contribution of the developed world. CO₂ has a residence time in the atmosphere of around 100 years (Hammond, 2000). The build-up of atmospheric concentrations is, therefore, largely a consequence of emissions released by countries of the North since the start of their so-called ‘industrial revolution’ around 1850. Thus, the industrialised nations should take a lead in mitigating the global release of GHGs, because they are principally responsible for their lifetime concentrations. Developing countries clearly desire to grow and provide a better ‘standard of living’ and enhanced well-being for their populations on equity or equality (*égalité*) grounds. They typically find suitable climate change mitigation measures prohibitively expensive. In addition, many rapidly emerging economies (like China and India) are currently more dependent on ‘dirty’ fuels, like wood and coal, and this results in their relatively high carbon ratios (Hammond, 2006; Cranston et al., 2010). Consequently, they could benefit from the assistance of industrial countries to promote their economic growth (which will, in time, induce a ‘demographic transition’ (Nakicenovic et al., 2000)), as well as leading to an improvement in the resource efficiency of their energy systems. Environmental sustainability (*sustainability*) could thereby be aided via the transfer of best practice (or ‘leapfrog’) energy technologies from the richer (Northern) to poorer (Southern) regions. These issues are at the heart of international negotiations aimed at providing a successor to the Kyoto Protocol, originally established to stabilise GHG concentrations at a level that would prevent dangerous climate change. A new agreement will hopefully come into being post-2012 that will ensure a sustainable future for the people and wildlife on ‘Spaceship Earth’ (Hammond, 2000). This will ultimately be in the interests of all its citizens (*fraternité*) and species.

Acknowledgements

This is a revised and updated version of a paper originally presented at the *Global Conference on Global Warming* (GCGW-09) in Istanbul, Turkey, over 5–9 July 2009 (denoted then as paper GCGW-09-400). The contribution of the first author (GRC) has been supported by the University of Bath's Strategic Investment Fund. The second author's research (GPH) on energy, environment and sustainable development has recently been supported by research awards and contracts in the UK from the *Biotechnology and Biological Sciences Research Council* (BBSRC) (as part of the *BBSRC Sustainable Bioenergy Centre* (BSBEC)), the *Carbon Trust*, *e.on UK* (the electricity generator), the *Engineering and Physical Sciences Research Council* (EPSRC), the *Environment Agency*, the *Great Western Research* (GWR) *Alliance*, and the *UK Energy Research Centre* (UKERC). He is presently the co-leader of a consortium of eight university partners (jointly with Professor Peter Pearson, an energy economist, now Director of the *Low Carbon Research Institute* in Wales) funded via the *e.on*/EPSRC Strategic Partnership to study the role of electricity within the context of "*Transition Pathways to a Low Carbon Economy*" (under Grant EP/F022832/1). The work of this consortium has been particularly influential in focusing his attention on low carbon development into the 21st century, albeit principally in the UK context. Both authors acknowledge the use of a 'strapline' in the title adapted from the national motto of the French Republic, and originally utilised in the present form by the *Fairtrade Foundation* in the UK (2009). The authors are grateful to Gill Green (University of Bath) for help in the preparation of figures.

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Appendix

The Kaya identity (see equation (1)) has been mathematically manipulated for this study, and rearranged in the following steps:

$$C = P \times G \times F$$

$$\log C = \log P + \log G + \log F.$$

The prefix 'log' refers here to natural logarithms. Differentiating with respect to time yields:

$$\frac{1}{C} \frac{dC}{dt} = \frac{1}{P} \frac{dP}{dt} + \frac{1}{G} \frac{dG}{dt} + \frac{1}{F} \frac{dF}{dt}$$

$$\frac{dC}{C} = \frac{dP}{P} + \frac{dG}{G} + \frac{dF}{F}.$$

APPENDIX B

DEFINITION OF SRES WORLD REGIONS

Source: Nakicenovic et al. (2000)

OECD90 REGION

North America (NAM)

Canada	United States of America
Guam	Virgin Islands
Puerto Rico	

Western Europe (WEU)

Andorra	Ireland
Austria	Isle of Man
Azores	Italy
Belgium	Liechtenstein
Canary Islands	Luxembourg
Channel Islands	Madeira
Cyprus	Malta
Denmark	Monaco
Faeroe	Netherlands
Islands	Norway
Finland	Portugal
France	Spain
Germany	Sweden
Gibraltar	Switzerland
Greece	Turkey
Greenland	
Iceland	

Pacific OECD (PAO)

Australia	New Zealand
Japan	

REF REGION

(countries undergoing economic reform)

Central and Eastern Europe (EEU)

Albania	Hungary
Bosnia and Herzegovina	Poland
Bulgaria	Romania
Croatia	Slovak Republic
Czech Republic	Slovenia
The former Yugoslav Republic of Macedonia	Yugoslavia

Newly independent states (NIS) of the former Soviet Union (FSU)

ASIA REGION

Centrally planned Asia and China (CPA)

Cambodia	Laos (PDR)
China	Mongolia
Hong Kong	Viet Nam
Korea (DPR)	
South Asia (SAS)	

Afghanistan	
Bangladesh	Maldives
Bhutan	Nepal
India	Pakistan
	Sri Lanka

Other Pacific Asia (PAS)

American Samoa	
Brunei Darussalam	
Fiji	Philippines
French Polynesia	Republic of Korea
Gilbert-Kiribati	Singapore
Indonesia	Solomon Islands
Malaysia	Taiwan, province of China
Myanmar	Thailand
New Caledonia	Tonga
Papua New Guinea	Vanuatu
	Western Samoa

ALM REGION (Africa and Latin America)

Middle East and North Africa (MEA)

Algeria	Morocco
Bahrain	Oman
Egypt (Arab Republic)	Qatar
Iraq	Saudi Arabia
Iran (Islamic Republic)	Sudan
Israel	Syria (Arab Republic)
Jordan	Tunisia
Kuwait	United Arab Emirates
Lebanon	Yemen
Libya/SPLAJ	

Latin America and the Caribbean (LAM)

Armenia	Lithuania	Antigua and Barbuda	Guyana
Azerbaijan	Republic of Moldova	Argentina	Haiti
Belarus	Russian Federation	Bahamas	Honduras
Estonia	Tajikistan	Barbados	Jamaica
Georgia	Turkmenistan	Belize	Martinique
Kazakhstan	Ukraine	Bermuda	Mexico
Kyrgyzstan	Uzbekistan	Bolivia	Netherlands
Latvia		Brazil	Antilles
		Chile	Nicaragua
		Colombia	Panama
		Costa Rica	Paraguay
		Cuba	Peru
		Dominica	Saint Kitts and Nevis
		Dominican Republic	Santa Lucia
		Ecuador	Saint Vincent and the
		El Salvador	Grenadines
		French Guyana	Suriname
		Grenada	Trinidad and Tobago
		Guadeloupe	Uruguay
		Guatemala	Venezuela
		<i>Sub-Saharan Africa (AFR)</i>	
		Angola	Malawi
		Benin	Mali
		Botswana	Mauritania
		British Indian Ocean	Mauritius
		Territory	
		Burkina Faso	Mozambique
		Burundi	Namibia
		Cameroon	Niger
		Cape Verde	Nigeria
		Central African Republic	Reunion
		Chad	Rwanda
		Comoros	Sao Tome and Principe
		Cote d'Ivoire	Senegal
		Congo	Seychelles
		Djibouti	Sierra Leone
		Equatorial Guinea	Somalia
		Eritrea	South Africa
		Ethiopia	Saint Helena
		Gabon	Swaziland
		Gambia	Tanzania
		Ghana	Togo
		Guinea	Uganda
		Guinea-Bissau	Zaire
		Kenya	Zambia
		Lesotho	Zimbabwe
		Liberia	
		Madagascar	

APPENDIX C

DIMENSIONAL ANALYSIS EXAMPLE

Dimensional analysis is a useful technique that enables information about a phenomenon to be deduced based upon a dimensionally correct equation with certain variables. The hypothesis states that the solution of a problem may be expressed by means of a dimensionally homogeneous equation in terms of specific variables (Langhaar, 1951).

A function can be formulated containing many variables and dimensional analysis is utilised to determine the details of the final expression. The nature of dimensional analysis can be explained through the use of an example.

Dimensional analysis is commonly applied in engineering and the sciences, thus an example is taken from this field.

Example

Nuclear explosions create shock waves. After a given period of time this shock wave assumes a spherical shape, with a radius R . Parameters are considered to be the initial energy of the blast, E , air density, ρ and time, t . Dimensional analysis can be used to establish the relationship between the radius of the shock wave and the other independent variables.

$$R = f(E, \rho, t) \quad \text{C-1}$$

These variables can be separated in terms of their dimensions, length (L), mass (M) and time (T), where $[.]$ represents the dimensions of each parameter:

$$R = [L] \quad E = \left[\frac{ML^2}{T^2} \right] \quad \rho = \left[\frac{M}{L^3} \right] \quad t = [T]$$

These can be written as a dimensionless group, following Buckingham's Pi theorem such that $f(\pi)=0$ where π is given by

$$\pi = R E^a \rho^b t^c = M^0 L^0 T^0 \quad \text{C-2}$$

for some values of a, b, c .

This can be solved by balancing the exponents:

$$\text{L:} \quad 1 + 2a - 3b = 0 \quad \therefore a = -\frac{1}{5}$$

$$\text{M:} \quad a + b = 0 \quad \therefore b = \frac{1}{5}$$

$$\text{T:} \quad -2a + c = 0 \quad \therefore c = -\frac{2}{5}$$

Substituting this into equation C-2:

$$\begin{aligned} \pi &= R \, E^{-1/5} \rho^{1/5} t^{-2/5} \\ &= R \left(\frac{\rho}{Et^2} \right)^{1/5} \end{aligned} \quad \text{C-3}$$

The relationship between the radius and the other variables can be expressed thus:

$$R = c \left(\frac{Et^2}{\rho} \right)^{1/5} \quad \text{C-4}$$

Where c is a constant.

This worked example highlights the use of dimensional analysis in determining a final expression relating a dependent factor with independent determinants.